Fire Safety Aspects of Polymeric Materials

VOLUME 6

AIRCRAFT: CIVIL AND MILITARY

A Report by
National Materials Advisory Board
National Academy of Sciences

(1)

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AIRCRAFT: CIVIL AND MILITARY

Report of

The Committee on Fire Safety
Aspects of Polymeric Materials

NATIONAL MATERIALS ADVISORY BOARD
Commission on Sociotechnical Systems
National Research Council

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VOLUME 6 – AIRCRAFT: CIVIL AND MILITARY

Fire Safety Aspects of Polymeric Materials

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NOTICE

The project that is the subject of this report was approved by the Governing Board of the National Research Council, whose members are drawn from the Councils of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine. The members of the Committee responsible for the report were chosen for their special competences and with regard for appropriate balance.

This report has been reviewed by a group other than the authors according to procedures approved by a Report Review Committee consisting of members of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine.

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FOREWORD

This volume is one of a series of reports on the fire safety aspects of polymeric materials. The work reported here represents the results of the first in-depth study of this important subject. The investigation was carried out by a committee of distinguished polymer and fire technology scholars appointed by the National Academy of Sciences and operating under the aegis of the National Materials Advisory Board, a unit of the Commission on Sociotechnical Systems of the National Research Council.

Polymers are a large class of materials, most new members of which are man-made. While their versatility is demonstrated daily by their rapidly burgeoning use, there is still much that is not known or not widely understood about their properties. In particular, the burning characteristics of polymers are only now being fully appreciated and the present study is a landmark in the understanding of the fire safety of these ubiquitous materials.

In the first volumes of this series the committee has identified the limits of man's knowledge of the combustibility of the growing number of polymeric materials used commercially, the nature of the by-products of that combustion and how fire behavior in these systems may be measured and predicted. The later volumes deal with the specific applications of polymeric materials, and in all cases the committee has put forth useful recommendations as to the direction for future actions to make the use of these materials safer for society.

In this volume on *Aircraft (Civil and Military)* the committee addresses the flammability of polymers used in aircraft cabins and pays particular attention to the special hazards of the smoke and toxic fumes emitted when they burn. In doing so, they have identified some important new questions which should be considered by others in a broader context. The study does not address the risk of aircraft fire per se; the findings of this study must be assessed by the appropriate agencies in terms of risk analysis and cost/benefit analyses to reach policy decisions as to total aircraft fire hazard.

Harvey Brooks, Chairman
Commission on Sociotechnical Systems

ABSTRACT

This is the sixth volume in a series. The fire safety aspects of polymeric materials are examined with primary emphasis on human survival. Other volumes in the series deal with materials: state of the art, test methods, specifications and standards, special problems of smoke and toxicity, fire dynamics and scenarios, and applications to buildings, vehicles, ships, mines and bunkers. An executive summary volume has been added to the series.

A study has been made of fire safety aspects of polymeric materials used in military and civil aircraft. After a preliminary system analysis, fire incident scenarios based on actual experience (but not reproducing any single fire) were devised. The problem of human survival in case of aircraft fire were assessed in terms of materials, test methods used to evaluate materials, smoke and toxicity, fire dynamics, and design use of materials. Conclusions are drawn in each chapter and appropriate implementable recommendations made. The majority of recommendations are extracted and combined in Chapter 2.

VOLUMES OF THIS SERIES

Volume 1	Materials: State of the Art
Volume 2	Test Methods, Specifications, Standards, Glossary
Volume 3	Smoke and Toxicity
Volume 4	Fire Dynamics and Scenarios
Volume 5	Executive Summary
Volume 7	Buildings
Volume 8	Vehicles — Railed and Unrailed
Volume 9	Ships
Volume 10	Mines and Bunkers

PREFACE

The National Materials Advisory Board (NMAB) of the Commission on Sociotechnical Systems, National Research Council, was asked by the Department of Defense Office of Research and Engineering and the National Aeronautics and Space Administration to "initiate a broad survey of fire-suppressant polymeric materials for use in aeronautical and space vehicles, to identify needs and opportunities, assess the state of the art in fire retardant polymers (including available materials, production, costs, data requirements, methods of test and toxicity problems), and describe a comprehensive program of research and development needed to update the technology and accelerate application where advantages will accrue in performance and economy."

In accordance with its usual practice, the NMAB convened representatives of the requesting agencies and other agencies known to be working in the field to determine how, in the national interest, the project might best be undertaken. It was quickly learned that wide duplication of interest exists. At the request of other agencies, sponsorship was made available to all government departments and agencies with an interest in fire safety. Concurrently, the scope of the project was broadened to take account of the needs enunciated by the new sponsors as well as those of the original sponsors.

The total list of sponsors of this study now comprises Department of Agriculture, Department of Commerce (National Bureau of Standards). Department of Interior (Design of Mine Safety), Department of Housing and Urban Development, Department of Health, Education and Welfare (National Institute for Occupational Safety and Health), Department of Transportation (Federal Aviation Administration, Coast Guard), Energy Research and Development Administration, Consumer Product Safety Commission, Environmental Protection Agency, and Postal Service, as well as the original.

The Committee was originally constituted on November 30, 1972. The membership was expanded to its present status on July 26, 1973. The new scope was established after presentation of reports by liaison representatives covered needs, views of problem areas, current activities, future plans, and relevant resource materials. Tutorial presentations were made at meetings held in the Academy and during site visits, when the Committee or its panel met with experts and organizations concerned with fire safety aspects of polymeric materials. These site visits (upwards of a dozen) were an important feature of the Committee's search for authentic information. Additional inputs of foreign fire technology were supplied by the U.S. Army Foreign Science and Technology Center and NMAB Staff.

A glossary of the terms used in the report of this Committee was compiled and will be found in Volume 2 (NMAB 318-2) of this series.

This study in its various aspects is addressed to those who formulate policy and allocate resources. A sufficient data base and bibliography has been supplied to indicate the breadth of this study.

ACKNOWLEDGEMENTS

This report was drafted by panels consisting of members of the National Materials Advisory Board Committee on Fire Safety Aspects of Polymeric Materials as well as government liaison representatives and was reviewed and finalized by the entire Committee. The conclusions and recommendations are the sole responsibility of the Committee. Coordination of this volume was performed by Rear Admiral W. C. Hushing, USN (Ret.).

A number of people made substantial contributions to this volume in addition to the members and liaison representatives who participated in the study. Some of these were professional colleagues of the Committee participants who served unofficially lending their ideas, advice and assistance to various portions of the work. Others were official guests of the Committee and contributed tutorial presentations; these individuals include: Messrs. S. Martin and N. Fishman, Stanford Research Institute; Profs. E. R. F. W. Crossman, P. J. Pagni, R. F. Sawyer, and staff, University of California, Berkeley; Lt. L. Orphanides, Army Foreign Science and Technology Center; Dr. L. J. Hillenbrand, Battelle Memorial Institute; Mr. J. Hamilton, NASA; Mr. C. Yuill, Southwest Research Institute; Mr. A. Routely, British Central Dockyard Laboratory; Dr. J. DeRis and Messrs. P. E. Cotton, J. M. Rhodes, and W. P. Thomas, Factory Mutual Research Corporation; personnel of the U.S. Army Natick Laboratories; Messrs S. Sarkos and E. Nicholas, Federal Aviation Administration; Dr. W. Berl, Applied Physics Laboratory, the Johns Hopkins University; Dr. H. Van Olphen, Numerical Data Advisory Board/National Research Council; Mr. R. Wands, Advisory Center on Toxicology/National Research Council; Mr. H. Nelson, General Services Administration; Messrs. M r. J. Klein, C. Giori, E. Raisen, H. Reilich, J. Stockham, and T. E. Waterman, Illinois Institute of Technology Research Institute (IITRI); Messrs. E. N. Laboratories; Mr. S. Riccitello, National Aeronautics and Space Administration, Ames; Dr. M. L. Grunnet and Dr. J. D. Sedar, Flammability Center, University of Utah. The Committee wishes to express its appreciation to these people.

The technical presentations covering current problems and needs for polymeric materials in aircraft, made by the liaison representatives of the National Aeronautics and Space Administration, the U.S. Air Force, U.S. Army, U.S. Navy, and Federal Aviation Administration, have been highly useful in establishing the overall goals for this volume.

Special thanks are due to three airframe manufacturers and five airlines that supplied bills of materials, details of engineering usage, and hazard analyses for the Committee's use.* The assistance of the Aerospace Industries Association is acknowledged with thanks as is the help of the Airline Pilot Association.

I acknowledge with gratitude the assistance in this project of Dr. Robert S. Shane, NMAB, Staff Scientist, and Miss Carolyn Tuchis, our able secretary.

Dr. Herman F. Mark, Chairman

*The participating airframe manufacturers were Boeing Company, Mc Donnell-Douglas Company, and Lockneed Aircraft Corporation. The airlines were United Airlines, Inc., Trans World Airlines, Inc., American Airlines, Inc., Pan American Airlines, Inc., and Allegheny Airlines, Inc.

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CHAPTER 1

INTRODUCTION

1.1 Scope and Methodology of the Study

The charge to the NMAB Committee on Fire Safety Aspects of Polymeric Materials was set forth in presentations made by the various sponsoring agencies. Early in its deliberations, however, the committee concluded that its original charge required some modification and expansion if the crucial issues were to be fully examined and the needs of the sponsoring organizations filled. Accordingly, it was agreed that the committee would direct its attention to the behavior of polymeric materials in a fire situation with special emphasis on human-safety considerations. Excluded from consideration were firefighting, therapy after fire-caused injury, and mechanical aspects of design not related to fire safety.

The work of the committee includes (1) a survey of the state of pertinent knowledge; (2) identification of gaps in that knowledge; (3) identification of work in progress; (4) evaluation of work as it relates to the identified gaps; (5) development of conclusions; (6) formulation of recommendations for action by appropriate public and private agencies; and (7) estimation, when appropriate, of the benefits that might accrue through implementation of the recommendations. Within this framework, functional areas were addressed as they relate to specific situations; end uses were considered when fire was a design consideration and the end uses are of concern to the sponsors of the study.

Attention was given to natural and synthetic polymeric materials primarily in terms of their composition, structure, relation to processing, and geometry (i.e., film, foam, fiber, etc.), but special aspects relating to their incorporation into an end-use component or structure also were included. Test methods, specifications, definitions, and standards that deal with the foregoing were considered. Regulations, however, were dealt with only in relation to end uses.

The products of combustion, including smoke and toxic substances, were considered in terms of their effects of human safety; morbidity and mortality were treated only as a function of the materials found among the products of combustion. The question of potential exposure to fire-retardant polymers, including skin contact, in situations not including pyrolysis and combustion were addressed as deemed appropriate by the committee in relation to various end uses.

In an effort to clarify the understanding of the phenomena accompanying fire, consideration was given to the mechanics of mass and energy transfer (fire dynamics). The opportunity to develop one or more scenarios to guide thinking was provided; however, as noted above, firefighting was not considered. To assist those who might use natural or synthetic polymers in components or structures, consideration also was given to design principles and criteria.

In organizing its work, the committee concluded that its analysis of the fire

safety of polymeric materials should consider the materials themselves, the fire dynamics situation, and the large societal systems affected. This decision led to the development of a reporting structure that provides for separate treatment of the technical-functional aspects of the problem and the aspects of product end use.

Accordingly, as the committee completes segments of its work, it plans to present its findings in the following five disciplinary and five end use reports:

Volume 1	Materials – State of the Art
Volume 2	Test Methods, Specifications, and Standards-Glossary
Volume 3	Special Problems of Smoke and Toxicity
Volume 4	Fire Dynamics and Scenarios
Volume 5	Executive Summary
Volume 6	Aircraft (Civil and Military)
Volume 7	Residential, Non-Residential and Custodial Buildings
Volume 8	Railed and Unrailed Vehicles
Volume 9	Ships
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Some of the polymer applications and characteristics are in the classified literature, and the members of the committee with security clearances believed that this information could best be handled by special meetings and addendum reports to be prepared after the basic report volumes were completed. Thus, the bulk of the output of the committee would be freely available to the public. Considering the breadth of the fire safety problem, it is believed that exclusion of classified information at this time will not materially affect the committee's conclusions.

1.2 Scope and Limitations of This Report

This report, Volume 6 in the series, specifically examines the polymeric materials used in commercial and military aircraft. For each category of aircraft, the Committee has attempted to determine

1. The parameters, physical and chemical, that influence flammability, smoke, and toxicity.
2. The material combinations, physical and chemical, that are used.
3. The use of the materials in devices, subsystems, and systems.
4. The geometry, position, and environment of the material.
5. The contribution of the materials to system performance in normal and abnormal modes (fire).

Since much knowledge needed to make such determinations was lacking, the judgements of the Committee are tentative and subject to revision; they represent only "best estimates possible" based on what is currently known (Inputs on aircraft

were delivered to the Committee before October 1974, and literature references beyond that date generally are not included). Additionally, it should be noted that while liaison representatives of sponsoring organizations attended the Committee meetings bringing with them a wealth of data, background, and experience, the Committee itself is solely responsible for the conclusions and recommendations presented in this report.

Although the relative priority of conclusions and recommendations was part of the Committee's discussions, this report does not attempt to advise managers of resources on how to allocate them, vis-a-vis other demands on those resources.

Specific polymeric materials generally excluded from this report include (1) fuel, (2) engine lubricants and other engine polymers, and (3) hydraulic fluids (but included are all other polymers in the hydraulic system, e.g., gaskets and diaphragms). Post-use disposal of polymers from aircraft production and obsolescence is not addressed in this report because of the relatively small amount of material involved (this matter is touched on in Volume 1, Materials: State of the Art).

Recognizing the seriousness of the problem of fire safety of materials in all segments of society, the Committee concluded that its work would be of value only if placed on the context of societal problems and their solutions. Accordingly, the Committee assessed polymeric materials used in aircraft relative to

1. Current materials knowledge and data
2. Current test methods and standards
3. Real world fire environments
4. Status of knowledge of smoke and toxicity
5. Systems applications
6. Potential for improvements

The Committee agreed on the nature of existing problems and deficiencies, but had some differences of opinion regarding the various solutions proposed and their priorities. It has nevertheless attempted to present a rounded picture of the present situation and what it believes to be the best current view in its conclusions and recommendations.

1.3 Committee Viewpoints

Members of the Committee are involved with materials research and development, applications, system design and evaluation; and liaison representatives deal with research and development, regulation, procurement, operations, and analysis. Thus, aspects of each material (and its problems) were subjected to a full spectrum of expertise. Full and extensive communication over the lengthy period of the Committee's operation provided an unusual base for augmentation of the expertise and rounding of knowledge.

Many statements about the fire safety aspects of polymeric materials appear in each of the reports published as a result of the Committee's study. Members of the Committee wish to emphasize that such statements, including judgmental ones in regard to fire safety aspects of materials, especially end uses, apply only to the

specific situations that pertain (e.g., suitability of a material from a fire safety point of view depends on many factors, including ease of access, ease of occupant egress, proximity of ignition hazard, proximity of other materials, thermal flux and duration of ignition source, ambient oxygen partial pressure, and fire and smoke detection and suppression systems in place).*

Statements in this volume must not be taken out of context and applied to the use of identical materials in other situations. In addition, the changing nature of the problem as time goes on and additional experience is acquired must be recognized by the reader as it was by the Committee. This viewpoint must be emphasized so that information that appears in all published reports of this Committee's study is not misused by taking it out of context.

*This list is not all-inclusive, but only indicative of the kinds of concerns that must be considered in making a materials selection.

CHAPTER 2

SUMMARY OF CONCLUSIONS AND RECOMMENDATIONS

2.1 Introduction

Fire safety aspects of polymeric materials used in aircraft present highly complex problems for which our society currently has few absolute solutions. Thus, it is necessary to evaluate the available technology and data base and use them to reach empirical decisions.

The large number of polymers used in aircraft and the special conditions of the aircraft in flight (i. e., self-contained ambient, no egress possible, etc.) as well as the limited knowledge of polymer performance under the wide variety of possible fire conditions necessitate a careful, disciplined problem-solving methodology utilizing the professional opinions of the nation's top experts in the field. This Committee has attempted such an approach.

2.2 General Conclusions and Recommendations

The United States is a leader in the production of large commercial aircraft. The aircraft manufacturers have consistently met or anticipated the performance needs of the air transportation system. No other industry has exceeded their concern for reliability and safety, and because of their concern the aircraft produced have improved continuously. The airline operators, their skilled air crews, and ground support teams generally have provided excellent service. Government regulatory and research activities usually have provided enlightened direction and technical assistance in the interest of improved services and increased safety to the public. Military transport aircraft are similar to large commercial aircraft and have similar attributes. Other military aircraft, developed to meet defense requirements, operate in a harsher environment. The Department of Defense and its component services have contributed substantial leadership to the development of aircraft and to improved safety in their design and operation. It is in this context of a relatively reliable and safe aircraft system tha the Committee makes its comments and suggestions.

Although the fire-safety record in commercial and military transport aircraft has been continuously improved, aircraft fires that cause human suffering and loss of life still occur. Because aircraft are carrying increasingly larger numbers of passengers, severe fires may cause proportionately more suffering and damage, and an attempt must be made to solve or alleviate this situation with state-of-the-art technology or by new developments. Thus, additional resources must be applied and emphasis given to the development of materials tests, and fire prevention and control methodology to provide improved fire safety.

It must be recognized that aircraft passengers bring on board a large fire load that should be better controlled or neutralized. Passenger behavior (smoking, trash

disposal, etc.) also should be better regulated if fire safety is to improve.

Considering all presently evaluated factors, it is impossible to provide a rationale for improving fire safety of aircraft solely by choice of polymeric materials from those now commercially available. Rather, it is necessary to consider the various subsystems of the aircraft in their operating and non-operating modes and, from these considerations, develop designated operating procedures that minimize risk while new materials are being developed and tested.

The more recently improved materials placed in use by the aircraft industry represent a step forward in fire-retardant characteristics. However, a growing concern exists that potentially hazardous effects, principally the toxic effects of combustion products, constitute a risk that could, under some circumstances, be significantly worse than fire (heat and flame) alone.

Better test methods for evaluating the fire resistance of materials are needed, particularly in simulating dynamic fire growth and full-scale real-life fires. The relationship of factors other than the composition of the polymer (geometry, ventilation, environmental oxygen, temperature, etc.) contributing to fire are relatively unknown.

Reliable risk assessment methods have not been developed and systematically applied. Development of generalized fire scenarios to be used in analysis and development of fire prevention and control methods should be undertaken and given a high priority.

Heat, pyrolytic gases, smoke, and panic all threaten survival when fire develops in a confined space such as an airplane. Aircraft fires are especially hazardous because of the unavoidable need for large quantities of highly flammable fuel on board, limited exit facilities, and frequently, a high population density. Increased awareness of fire hazard is a part of aircraft design; development of methods for fire detection and procedures for suppressing aircraft fires must have high priority.

2.3 Specific Conclusions and Recommendations

2.3.1 Fire Dynamics and Scenarios

Designers and builders of aircraft today need a stronger basis for the risk assessment and trade-off studies that are clearly needed as a part of the building-operation sequence. Availability of detailed and reliable scenarios can supply this basis.

Scenarios are beneficial, not only as aids in analyzing specific accidents but also as guides to designers of aircraft on materials selection and design modifications. In addition, detailed fire scenarios are useful in developing realistic fire test methods and setting standards. Unfortunately, many current tests and standards were not developed within the framework of realistic fire conditions. Fire scenarios can guide the formulation of regulations and planning of meaningful research programs.

A major reason for developing detailed aircraft fire scenarios is to help pre-

vent future fires and limit the loss of life, injury, or damage caused by fire. Thus, in-depth analyses of detailed fire scenarios should provide essential information to the aircraft designer.

While materials selection and arrangement play a major role in the prevention and control of aircraft fires, other elements, totally unrelated to polymeric materials, are extremely important. Prevention can be enhanced by proper education, more stringent regulations, and modified operating procedures. Control is strongly influenced by the absence or presence of adequate detection, extinguishment, and life support systems. These additional factors must not be neglected; therefore, an overall systems approach is necessary to decrease the hazard of fire on aircraft.

A major inadequacy is the lack of sufficiently detailed scenarios to direct optimum fire-safety design of aircraft. Furthermore, fire scenarios developed solely on the basis of accident investigations would be inadequate to achieve this objective. Generalized scenarios (as outlied in Section 3.3) based on real or credible incidents should be developed. The specific events in these scenarios (e.g., rate of fire spread, heat release) should be further quantified by information obtained from large-scale experiments. (Ultimately, this procedure should result in the development of analytical models for use in predicting fire hazard and the need for expensive large-scale experiments will be eliminated.) It must be noted, however, that information from actual aircraft fire incidents needed for such scenarios is incomplete and not readily available; information that is available generally provides an insufficient basis for useful scenarios. The reason is inadequate collection and reporting of field data; therefore, accident investigation teams should utilize the general model of scenario development presented in Section 3.3 to ensure that all essential elements of a fire scenario are adequately addressed in their accident reports. In addition, the National Transportation Safety Board (NTSB) should broaden its coverage to include minor and incipient fires, including those that do not cause injury or structural damage, and should act more rapidly in disseminating the information it collects.

The application of fire scenario analysis to improve aircraft safety is the most productive methodology for dealing with the complex aircraft system. Scenarios, therefore, should be used for the analysis of fire hazard and for the development of methods to provide increased survivability. In particular scenarios should provide bases for (1) materials selection; (2) design criteria; (3) validation of test methods; (4) promulgation of regulations; (5) personnel training; and (6) research and development objectives.

2.3.2 Aircraft Design and Operation

The problem of fire safety in aircraft is unique because of the limited egress capability afforded passengers and crew. There is no egress available to passengers and crew of a commercial aircraft in flight. For this reason, a systems approach to fire safety was employed for the investigation, evaluation, and subsequent recommendations for fire safety of the total vehicle system. The resulting conclusions and

recommendations therefore reflect, to a great extent, fire prevention as well as fire containment considerations. In this context, a positive approach for improving the fire-safety aspects of the airplane system is recommended to include the following:

1. Development of fire scenarios to provide the reference base needed for use as a system design tool as well as the analyses and trade-off studies that will generate a better tool.

2. Fire hardening of fire-prone areas to improve fire-retardant qualities and decrease toxicity (especially those particularly susceptible to rapid fire spread, such as galleys and lavatories).

3. Further eliminating fire ignition sources and reducing the fire load through the prohibition of all smoking in aircraft cabins and lavatories and the introduction of the use of rubbish compactors for trash stowage during flight.

4. Detecting fires in the early stages of development through the provision of fire and smoke detection equipment in areas occupied by crew and passengers as well as those spaces not normally occupied by humans (e. g., cargo holds).

5. Requiring airline flight crews to wear clothing fabricated from commercially available fire-retardant fibers.

6. Completely reviewing existing passenger emergency oxygen systems in terms of their respective safety and purpose (i. e., for use during emergency decompression) as well as from the standpoint of providing oxygen mask systems that prevent the inhalation of smoke and toxic gases and that can be used during the evacuation of the aircraft.

Analyzing the use of crashworthy fuel systems in commercial transport aircraft with a view toward taking advantage of U.S. Army experience in diminishing post-crash fire fatalities in aircraft equipped with such fuel systems.

2.3.3 Materials

Aircraft safety is affected by several factors operating in concert, the polymeric materials of construction representing only one facet. Fire prevention, fire detection, fire control, and fire-resistant materials must be considered as a system.

Many of the polymeric materials used in commercial and military aircraft are deficient from the fire safety point of view. Better materials are available for some purposes, and new materials not commercially available would be acceptable for other applications. However, for many areas, there are no materials that are completely suitable in all respects and informed trade-offs must be accepted.

The primary guidelines of economics, serviceability, and aesthetics have been coupled with the need to meet existing fire safety regulations. The use of available improved materials could be accelerated, however, by the issuance of more stringent regulations. New test methods are also needed to guide materials development and selection. The effects of smoke, heat, and toxic products of pyrolysis are particularly important since egress from an aircraft is limited or unavailable. These concerns have only recently received critical attention in the selection of materials.

SUMMARY OF CONCLUSIONS AND RECOMMENDATIONS

Polymeric materials used in the construction of aircraft galleys and lavatories, where a major portion of fires start, can be improved from the standpoint of ignition, flame spread, and smoke and toxic-emission threat.

Fire safety research on polymeric materials, supported by the government and industry is fragmented and is difficult to assess because of poor exchange of information. The division of responsibility for materials selection between airframe manufacturers and aircraft operators presents an interface problem.

The more extensive use of detector and extinguishment systems will decrease the consequences of polymeric materials flammability.

Materials carried on board by passengers contribute significantly to fire hazard and fire load.

Combinations of polymeric materials may behave more adversely under fire conditions than predicted from evaluation of individual components.

Fire safety of cabin interiors can be improved significantly by the selection of currently available char-forming materials, although improvements in fabrication methods are required for these materials.

Polyvinyl fluoride, covering large areas of the interior walls of many aircraft, represents a potential source of smoke and toxic gas during pyrolysis of combustion.

The flame-retardant epoxies used in wall composites can be the source of significant quantities of smoke.

Neoprene and/or urethane-coated nylon fabrics used in life vests, life rafts, and emergency slides are unsatisfactory with respect to ignition, flame spread, and smoke and toxic gas emission.

Polyurethane foam, and in particular flexible foam, used in aircraft is deficient in many fire safety aspects.

The use of carpets in the vertical position in aircraft as decorative material introduces an unnecessary fire hazard.

The contribution of the chemical oxygen generator system to the potential fire hazard of materials needs defining.

In light of this situation, the committee recommends that:

1. The replacement of present materials in new and remodeled aircraft interiors with available improved materials be accelerated.

2. Methods for risk and trade-off analysis be developed and employed in materials selection.

3. In existing aircraft, where practical, require replacement of existing materials with improved materials when a significant decrease in risk is established.

4. More meaningful flammability tests and methods for evaluation be developed to assist in materials development and choice.

5. Tests and guidelines for definition of toxic hazards from pyrolysis and combustion of polymeric materials be developed.

6. The coordination of fire safety-related materials programs and dissemination of information therefrom to all interested parties be improved.

7. Means be evolved to stimulate commercial development and availability of new materials that are superior from a fire safety point of view.

8. The split responsibility for materials selection and design between aircraft manufacturers and aircraft operators be resolved.

9. The research and development programs for thermal protection methodology and for hardening aircraft fuselage against the external fire threats be extended.

10. More stringent fire safety regulations be implemented.

11. The fire resistance of the existing polyurethane foam-based seating systems be improved through design, construction, and selection of covering materials.

12. A relatively fire-safe replacement for the existing polyurethane foam cushioning be developed.

13. The fabrication cost of large complex parts from char-forming materials be lowered.

14. Known hazardous textile materials used in aircraft interiors be replaced with available improved materials.

15. The toxic hazard from pyrolysis and combustion products of the polymeric materials used in aircraft interiors be defined.

16. The galley and lavatory areas be fire hardened.

17. Fire-safety coatings for base fabrics used in life rafts, life vests, and emergency slides be developed.

18. The use of organic fiber carpets in a vertical position be eliminated.

19. The fire safety of overhead duct insulation systems and/or choice of materials be improved.

20. The fire safety of wall and ceiling panels be improved through choice of materials or development of new materials when necessary.

21. The hazard of carry-on materials be defined and controlled.

22. Knowledge of the relationships of polymer structure and fire environments to the nature of pyrolysis and combustion products of polymers and combinations of materials be increased.

23. The contribution of emergency oxygen systems to the potential fire hazard of polymeric materials be defined.

2.3.4 Testing

In its assessment of the situation, the Committee has concluded that it is extremely questionable whether the "self-extinguishing" cabin and cargo compartment interior materials now provided by Federal Aviation Regulations and their specific test conditions represent minimum acceptable fire-safety level for aircraft certification based on today's knowledge. Current flame-resistant and self-extinguishing criteria neglect other important flammability characteristics of polymeric materials, especially smoke and toxic gas production. Current material flammability standards are based solely on "flame resistant" criteria which do not adequately represent the more severe fire hazard configuration or subject the mater-

ial to real fire conditions. Polymeric fuel additives show great potential for reducing the fire hazard from fuel spillage following a survivable crash, but test methods are lacking.

In view of its conclusions, the Committee recommends that:

1. Research be initiated to correlate test methods with fire hazard of polymeric interior cabin materials. Additional large-scale testing is required to provide the data base for validating small-scale tests and modified regulations should be promulgated if required.

2. ASTM E-162, the radiant panel test, should be employed to determine the "flame-resistance" of cabin and cargo compartment interior materials, since it more closely represents real fire conditions than do currently employed tests.

3. The vertical test should be employed for all cabin and cargo compartment interior fabric materials. Then the same level of fire resistance would be maintained for all fabric materials. Further, three separate tests, using flame application time of 3, 12, and 60 seconds should be employed in the vertical test.

4. Performance levels for acceptance in both the E-162 and vertical tests should be based on the responses of these materials in large-scale tests.

5. The NBS smoke density test (NFPA 258) is the most useful smoke test presently available and should be employed in a smoke standard for interior cabin materials. The variation of smoke production with heat flux should be evaluated.

6. The FAA should establish standards governing the toxic gas emission characteristics of compartment interior materials when subjected to real fire conditions; however, further research and study are necessary before this recommendation can be implemented.

7. The development of modified fuels should be continued, and a test method should be developed for screening modified fuel candidates under conditions that correlate with the most severe fuel release and ignition conditions expected in a survivable crash.

2.3.5 Smoke and Toxicity

At the present time the Committee believes that it is difficult to establish the degree to which combustion and thermal decomposition products from synthetic polymers on board aircraft are involved in hazards to human survival during aircraft fires. It is known, however, that deaths caused by toxic gases generated during in-flight and other aircraft fires have occurred in accidents that might have been otherwise survivable. Additionally, laboratory evidence indicates that smoke can be an important adverse factor in escape and survival due to obscuration of exits, lachrymation, and panic, as well as toxicity.

Although carbon monoxide is a major toxic hazard in polymer fires, current data indicate that under both clinical and experimental conditions thermal decomposition products other than CO may be involved in the hazard to human survival if certain types of polymer systems and/or fire-retarded polymers undergo com-

bustion or pyrolysis. Also, the investigation of the overall biological effect of polymer combustion products including synergism of the polymer combustion products to produce a graver effect than any acting alone has been inadequate in that autolytic (as opposed to pyrolytic) phenomena have been ignored *inter alia.*

In view of the conclusions, the Committee recommends that:

1. A research program be established in two or more qualified institutions to develop criteria and practices for determining the degree to which polymers contribute to human morbidity and mortality in aircraft fires.

2. Polymers be utilized that will meet structural, economic, and design requirements and offer the least life hazard in fire situations (the contribution to life hazard will generally depend on both the total amount and particular application of the polymeric material).

3. Attention be directed towards more extensive utilization of methods for fire detection in fire-susceptible areas on aircraft (e. g., galleys, lavatories and cargo holds).

4. The efficient and safe utilization as well as the toxicology of fire-suppressant chemicals to be more fully investigated.

5. The feasibility of using life support systems independent of the aircraft cabin atmosphere be assessed.

CHAPTER 3

FIRE DYNAMICS AND SCENARIOS (FAILURE MODE AND EFFECT ANALYSES)

3.1 Introduction

The physical, chemical, and thermal aspects of fire render it a complex phenomenon. Over several thousand years man has learned to use fire and, to some extent, control it, but many processes associated with ignition, combustion, and extinguishment of fire remain largely unknown. Practical solutions for many fire situations have been devised without full knowledge of the fundamental processes involved and their interrelationship; however, many of these solutions have been based only on post-fire analysis and this approach is no longer satisfactory.

Modern technology has provided us with larger and more sophisticated living and transportation units that have elaborate interiors and furnishings made from new polymeric materials. Sufficient knowledge about the fire safety aspects of these materials is lacking and, as a result, the potential danger to life and capital investment is high. Thus, development of a sophisticated approach to fire prevention, decision, and extinguishment has become a necessity, particularly in the case of the modern airplane.

Many empirical approaches to the problem have been developed, specifications and regulations written, and operating procedures established and implemented. The combined efforts of the manufacturers, operators, and government regulators of aircraft have resulted in a product whose technical performance is significantly superior to the product of many other industries.

Nevertheless, specifications relating to fire hazard, including potential toxic effects, normally are not included in the performance specifications for polymeric materials, and the development of fire-retardant materials has lagged seriously behind the rapid expansion in use of new synthetic polymeric materials. Thus, while today's commercial and military aircraft have a remarkable safety record, the greatly increased risk per accident resulting from use of larger sized aircraft necessitates an unflagging effort to eliminate or reduce the fire hazard including the effects of smoke and toxic combustion products.

There is no one best way to reduce the fire hazard in modern airplanes; but it is clear that any solution must be based upon knowledge of how materials choice, aircraft design, training, education and regulations affect the initiation and spread of fire in an aircraft. Unfortunately, scientific understanding of fire is presently inadequate to permit one to predict precisely how the substitution of one material for another or how a specific design modification will affect the overall hazard level on the aircraft. More information based on research investigations, large-scale realistic fire simulation experiments, and properly detailed reports of actual fires is

needed before such questions can be fully answered. In the interim, however, existing technology must be employed to minimize the fire hazard associated with modern aircraft.

Presented in this chapter are "Generalized Scenarios for Aircraft Fires" (Section 3.2) that, while hypothetical and not representing a one-to-one description of any specific fire, illustrate the potential threat to life safety from fire on an airplane as well as the value of scenarios in identifying means for reducing the hazard in commercial aircraft (e.g., through improved material selection and design; the addition of detection, extinguishment and life support systems; the institution of regulations). Reliability engineers might recognize scenarios as a form of failure mode and effect analysis.

Scenarios are beneficial both as aids in analyzing specific accidents and as guides to designers of aircraft on materials selection and design modifications. In addition, detailed fire scenarios that incorporate experience are useful in developing realistic fire test methods, setting standards (unfortunately, many current tests and standards were not developed within the framework of realistic fire conditions), formulating regulations, and planning meaningful research programs.

Scenarios have maximum utility if they: (1) represent accidents having high probability of causing a significant portion of the annual life loss from fire and (2) provide sufficiently detailed information to permit useful analysis. (Unfortunately, virtually all real fire investigations are handicapped by the absence of trained observers, especially at the early stages of the fire, so frequently one must guess what happened from fragmentary evidence.)

To indicate what information is desirable in the ideal fire scenario and to serve as a guide to those responsible for the preparation of specific accident reports, "Guidelines for Developing Fire Scenarios" are presented (Section 3.3) to identify the important factors generally present in an aircraft fire that results in catastrophic failure. The physical behavior of fire is emphasized and human behavior is deemphasized since this study stresses fire safety via materials selection and design considerations. This general model for fire scenario development also can assist in the design and monitoring of large-scale realistic fire simulation experiments.

Since the major reason for developing detailed aircraft fire scenarios is to prevent a future fire from developing or to limit the loss of life, injury, or damage caused by such a fire, "Guidelines for Analysis of Fire Scenarios in Aircraft" (Section 3.4) are presented. An in-depth analysis of detailed fire scenarios will provide essential information to the aircraft designer. While it is obvious that materials selection and arrangement can play a major role in the prevention and control of aircraft fires, there are other elements, totally unrelated to polymeric materials, which are extremely important. These additional factors must not be neglected since an overall systems approach is necessary to decrease the hazard due to fire on aircraft.

3.2 Generalized Synthetic Scenarios for Aircraft Fires (Based on Actual or Probable Incidents)

3.2.1 Ramp Fire

3.2.1.1 Description

The fire started from an electrical fault in a razor outlet in the left aft lavatory of a commercial jet transport parked at a passenger-loading gate at a metropolitan international airport.

The aircraft had arrived at the airport at 12:57 a.m. after a routine flight. Between 2:15 and 2:30 a.m. a cabin cleaner allowed some water to enter the shaver receptacle in the left aft lavatory (the cleaning was being done with an aqueous detergent-type solution). The resulting sparks and smoke lasted for only 2 or 3 seconds. The cleaner advised the heat mechanic on duty of the occurrence and finished cleaning, noticing no further smoke.

Sometime later a line mechanic was assigned to check the razor outlet on the aircraft. He apparently thought that the circuit breaker for the right forward lavatory razor outlet had "popped". (It was actually the circuit breaker for the shaver outlets in the aft lavatories). Sometime between 4:00 and 4:30 a.m. the mechanic, using standard trouble-shooting procedures, worked on the right forward lavatory razor outlet. He reset the circuit breaker, which again popped after approximately one minute, and then serviced the razor outlet to remove any moisture. He reset the breaker again and, as before, it stayed reset for about one minute and then popped. No work was done on the left aft lavatory circuit, the one actually affected, leaving one to conclude that the line mechanic's instructions had been inadequate or that he did not understand them.

Unable to fix the forward lavatory shaver outlet, the mechanic walked through the aircraft to check for any other occupants at about 4:45 a.m. He then left the aircraft unattended and disconnected the ground power unit to refuel it. He intended to later render the troublesome circuit inoperative.

It is estimated that about 4:20 a.m. electrical arcing during trouble-shooting ignited paper products that had fallen into the space behind the razor outlet from an adjacent towel and facial tissue dispenser located directly above the shaver receptacle. During this early stage the fire was in the concealed space behind and above the aft lavatory paneling and therefore not detected.

From this point of origin, the fire traveled up between the structural fuselage framing to the overhead ceiling area and forward in the undivided ceiling plenum area to a point about as far forward as the wing's trailing edge. There the fire diminished in intensity and seemed to be more below the ceiling panels than above. From the first class cabin divider forward to the cockpit door, flame penetration appeared to have resulted from a flashfire, with damage to the passenger service unit housing, disintegration of the vinyl coating on the hat racks and sidewall coverings, and damage to the ceiling panels. Smoke and soot penetrated the cockpit

in areas between the fuselage skin and paneling. Local intensification of the fire occurred when the thermal relief valves on the oxygen bottles in the hat racks operated. The first alarm was given at 5:03 a.m. when smoke was observed coming from the left forward entry door, the only door that was open at that time. The observer called for the fire department to be notified and attempted to enter the cabin, thinking the fire was in the cockpit area. In this attempt he encountered "yellow-black acid smoke" pouring from the cabin door that prevented entry to the cabin.

Other employees then attempted to attack the fire with dry chemical extinguishers through the aft right galley service door after obtaining a lift truck and opening that door. By then, a red glow had appeared at several cabin windows and the forward entry door was closed to prevent a "chimney effect" through the cabin, but the firefighting effort was unsuccessful. Clearly, the fire had progressed too far and had involved a major portion of the concealed spaces in the cabin.

The airport fire department received the alarm at 5:09 a.m. and at approximately 5:13 a.m. men with five pieces of fire equipment arrived at the scene. The equipment consisted of two 3,000-gallon crash trucks, two 2,300-gallon nurse trucks, and one 1,000-pound dry chemical unit. Four 2½ inch hose lines were later placed in use (one at the rear galley door, one at an over-wing exit, one through the forward entry door, and one through a window that had been punched out and through the rear door). The airport fire crew later received backup equipment from an off-airport fire section. About 5:30 a.m. the fire appeared to be extinguished. Fortunately there were no injuries or fatalities, but the direct moneyloss was calculated at about $900,000 and the aircraft was out of service for 3½ months.

3.2.1.2 Analysis

The aft right lavatory (door closed to the cabin) had received only heat and smoke damage and was inspected for comparison conditions. The razor outlet panel was removed. Detailed inspection of the aft left lavatory, where the fire was believed to have started, confirmed that an electrical short had been experienced at the 115-volt ac razor outlet; burned paper products were found around the outlet. As noted, the fire was concentrated first in the concealed space behind the razor panel and thentraveled up between the fuselage frames to the overhead ceiling area. An aluminum duct, supplying an "eyeball" air conditioning outlet in the lavatory, was melted at the point where it passed immediately above the razor outlet and the point of paper towel accumulation.

When the fire reached the concealed space above the drop ceiling in the lavatory, it entered an open channel without any fire divisions that extended above the cabin all the way forward to above the cockpit. The fire went around a water tank in the ceiling and then forward, breaking out of the dropped ceiling plenum into the area above the curved ceiling panels. Burned wiring bundles indicated the intensity of the fire in that area. Besides the paper toweling and tissues, combustibles available to burn include acrylonitrile butadiene styrene (ABS) or vinyl-type

thermoplastics, wiring insulation, wood frames for the vertical and ceiling panels, and neoprene/nylon vapor barrier covering the insulation blankets. Most of the wood frames were charred through near the place of fire origin. As noted above, only smoke had been noticed when the fire was first discovered and several minutes passed before flames were seen through the cabin windows. Thus, it is assumed that the fire burned through the ceiling and into the cabin about 5:10 a.m.

In the aft (tourist) section of the aircraft almost all the polymeric substances above the windowline in the passenger cabin burned. This was disturbing since the cabin had been redecorated in November 1968 to comply with the material requirements of current Federal Air Regulations (FAR 121.312). It was readily apparent that this fire imposed on the interior materials more severe conditions than those used in testing such materials for compliance with the regulatory specifications. The acrid smoke, produced by the cabin lining materials, and the wiring insulation prevented access for fire control. In the forward (first class) cabin, damage was far less severe.

The contribution to the fire from released oxygen was localized. Eight oxygen cyclinders were involved. While all showed different exposures to heat, all were found empty, the oxygen having escaped through the cylinder safety plugs.

Analysis of this scenario suggests the following remedial steps:

1. A barrier should be provided to prevent paper towels and other debris from entering the areas behind the razor outlets in the aft lavatory. Such material provided ready tinder for the fire when the electrical fault occurred.

2. Better shielding for lavatory electrical connections should be provided to prevent penetration of water or cleaning solutions. The shaver-power receptacle assembly design (with the wires routed up from the receptacle) permitted water or collected moisture to run down into the receptacle from the exposed side; moisture on the back of the panel assembly could run down from above and collect in the assembly. Water on the electrical connections was judged a major contributing factor in this fire.

3. The possibility of providing fire-retardant (metal char-forming foam or char-forming glass-resin composite) fire bulkheads at intervals in the concealed space above the drop ceiling and headliner should be investigated (giving due consideration to toxicity and smoke hazard). Such bulkheads would have either contained the fire or caused it to break out and reveal itself sooner, leading to earlier discovery and less damage. Most aircraft have undivided concealed spaces behind ceilings and headliners; this space may constitute as much as 15 percent of the total volume of the aircraft.

4. Cabin finishing materials that minimize flame spread, smoke emission, and generation of toxic gas should be selected. The fact that the fire occurred and grew so intense that it jeopardized the entire aircraft suggests that polymeric materials are vulnerable to undetected fires. The ignition source and the tinder were relatively small (no aircraft fuel was involved); yet the installed furnishings ignited readily and burned freely, demonstrating the inadequacy of current tests and standards.

3.2.2 In-Flight Fire in Unattended Area

3.2.2.1 Description

The fire started due to an undetected electrical short within the left nickel-cadmium aircraft battery sometime during a 54-minute regularly scheduled passenger flight. Nineteen passengers and three crew members were aboard the aircraft.

The flight departed at 4:30 p.m. on an instrument-flight-rules flight plan. Shortly after departure, the captain cancelled the flight plan and proceeded in accordance with a visual-flight-rules flight plan via the same route. The flight routine was uneventful until after the landing at an international airport. The airplane landed at approximately 5:24 p.m. During the landing roll-out the captain noticed an unusual odor and discussed it with the first officer. They decided that engine fumes coming from the fresh air inlet due to a quartering tailwind were the cause and the circulation fan was turned off. While waiting for another plane to land before proceeding to the terminal, the stewardess came forward and informed the captain that there was smoke in the vicinity of row 4 on the left side. Acting on the captain's orders, the first officer checked the cabin and verified the presence of smoke. At approximately 5:27 p.m. the crew requested ground control to check the right side of the aircraft for smoke. Prior to ground-control acknowledgement of this request, the flight crew transmitted, "shutting down, bring out the fire stuff." The captain stopped the aircraft immediately and ordered that the air stair door be opened. After the engines were shut down and all electrical switches were turned off, the first officer was ordered to proceed to the bottom of the stairs to direct passengers away from the aircraft. As the captain started to leave his seat, he noted that he could move the control wheel to full aft position although the control lock had been engaged about two minutes earlier following the landing roll-out. After all passengers had deplaned, the captain entered the partially smoke-filled cabin and made a positive check that everyone had evacuated. At no time did the captain observe any fire. The captain then deplaned and directed the passengers to an area further away from the aircraft. Airport emergency equipment arrived at this time and began to direct foam water into the cabin.

3.2.2.2 Analysis

The investigating team determined that the probable cause of this accident was an undetected electrical short within the left nickel-cadmium aircraft battery that resulted in absorption of an increasing amount of heat energy over an unknown period of time and progressed to a state of thermal runaway. The nickel-cadmium battery removed from the left side of the aircraft was severely charred and discolored by heat and fire. The polystyrene cell case material had melted and solidified in the bottom of the battery case. A solidified flow pattern of this material through the battery case viewing ports also was evident. All external battery case damage was above these viewing ports.

The near complete destruction of the battery precluded a determination of the mechanics of the internal failure that resulted in a thermal runaway. After considering the oeprational requirements and practices of the airline, in conjunction with an in-depth review of the maintenance program, it was concluded that company operational demands and maintenance procedures could be eliminated as contributing factors in this accident.

The air circulation pattern resulting from operation of this aircraft's pressurization system (it forces air from the cabin into the baggage compartments, and then overboard through the outflow valves located in the aft underside of the aircraft) makes it difficult to determine when the battery malfunction began. Smoke or fumes originating in the batteries during flight would dump overboard through normal air circulation and the odor would not enter the cockpit until after the aircraft had landed and the cabin pressurization system spill valves were opened. In this case, the crew smelled a burning odor while the recirculation fan was on after landing; however, when the fan was turned off the odor dissipated.

During landing roll-out and the subsequent taxi to the terminal with the battery in a state of thermal runaway, one or both of the following sequence of events developed: (1) the polystyrene cell case material heated by the thermal runaway ignited and emitted fire and smoke through the battery case viewing ports, or (2) the cell case material was heated to its decomposition temperature giving off highly flammable gaseous pyrolysis products which were ignited by the hot battery and in turn ignited the polystyrene cell cases. Smoke and fumes from the shorted battery then began to seep into the cabin through vent holes below the seat A windows at rows 4 and 5 and was observed by the seat occupants.

As mentioned above, the exact time of initial battery malfunction could not be ascertained. However, the flight control push rods located a short distance above the left battery had not been burned through at the time the flight control lock was engaged following landing roll-out. Therefore, these push rods were burned and melted by fire between the time the aircraft was turned from the landing runaway and the time the captain assisted himself out of his seat by pulling on the locked control yoke. The elapsed time between these two occurrences was approximately 2 minutes, which attests to the extreme intensity of the battery fire.

The aircraft interior was severely damaged by fire, heat, and smoke, The passenger compartment in the vicinity of row 4 received the most severe fire and heat damage, and the damage throughout the cabin was more extensive at the ceiling level than on the lower side wall structure. A hole of about 21 by 31 inches was burned through the wood floor below seat 4B, and damage to the area below the cabin floor was limited to the left side of the electrical compartment located immediately below row 4. That portion of the aileron, elevator, and rudder control push rods (approximately 16 inches) located about 11½ inches above the left battery had melted away, as did three floor-support stringers. Fuel and hydraulic systems, which could have fueled the fire showed no evidence of system leakage.

This accident was one of a series of nickel-cadmium battery fires in aircraft, and an analysis of the scenario suggests the following remedial steps:

(1) An in-depth program aimed at an analysis of these battery failures with a view toward discovery of the failure mechanism should be undertaken.

(2) As a result of this and other fires that have occurred aboard this type of aircraft, engineering changes to improve the fire safety in the electric bay region should be undertaken. Pending the completion of such engineering changes, the airline operators might:

a. Install steel flight control push rods in the electrical compartment area, thus lengthening service life before loss of function.
b. Shield the electrical components in the aft section of the electrical compartment.
c. Consider attachment of aluminum or steel reflector material to the underside of the cabin floor in the electrical compartment area or, alternatively, use of refractory insulation to contain fire and prevent flame and heat penetration through the floor.

3.2.3 Crash Fire With Fuselage Essentially Intact

3.2.3.1 Description

Following a routine flight the commercial jet air-liner made a normal approach in preparation for landing. Because the descent rate was too high, the main landing gear was torn off as ground contact was made and the aircraft skidded, colliding with ground objects. The landing impact, while severe enough to destroy the landing gear and jam some exit doors, did little structural damage to the fuselage and caused only relatively minor injuries to a few passengers. However, a few seconds after impact, fire started from a ruptured fuel line under the cabin floor. Within 90 seconds the entire cabin was engulfed in flames. Passengers sitting behind the egress hatches over the wing escaped with minor burns. During the fire a hole appeared in the crew cockpit, and the co-pilot and engineer escaped via this exit; the pilot did not have sufficient time to exit and perished due to intense smoke and heat. Although two airport fire trucks arrived about 3 minutes after impact, they were too late. Ninety-nine passengers did not have time to escape before being stricken by the fire; twenty-nine received minor injuries. The fuselage was completely destroyed by the fire.

3.2.3.2 Analysis

Take-off and landing are the most hazardous parts of a flight. Although constant attention is given to adherence to safety practices and accidents resulting from aborted take-offs and crash-landings are not frequent, there is, nevertheless, a continuing hazard. Many passengers often survive the impact in accidents of this nature, but in far too many cases, they die as a result of external fire fed by fuel. A strong influencing factor in the case of survivable crash is the possibility of structur-

al damage that would rupture the fuselage and admit fire.

The scene described in this scenario is a familiar one to crash-fire investigators who find that little time is required for fatal injuries to occur once a crash fire has started. Generally, passengers caught in an aircraft ground accident that has resulted in fire have only seconds to escape. Those failing to exit quickly die from exposure to heat and toxic gases. Because of the fire danger, rapid evacuation is stressed in all such accidents. Unfortunately, it is not always possible to evacuate an airliner fast enough to save all on board and as more of the larger wide-bodied airplanes capable of carrying several hundred passengers are put into service, quick evacuation in emergencies will remain a serious problem.

Due to the extremely rapid series of events in crash fires, it is impossible to accurately detail the exact conditions inside the aircraft. However, an instrumented full-scale test has been run that stimulates post-crash fire conditions. In this test, a fuselage section was taken from a surplus C-47 airplane. The fuselage was instrumented to measure the exterior and interior thermal environments as well as the intrusion of smoke and toxic gases. The fuselage was subjected to a JP-4 fuel fire, designed to envelop the fuselage completely with flames and to expose the vehicle to the maximum heat flux for 10 minutes.

Although the fuselage interior was obscured by dense smoke, motion pictures showed flame penetration within 1 minute after ignition. After 2 minutes, the section was completely destroyed. Air temperature in the cabin rose to 601°F (316°C) in less than 2 minutes after start of the fire and continued to climb rapidly as the section was destroyed. Within 30 seconds after ignition, smoke started to penetrate the interior, to survive occupants of the cabin would have had to have been evacuated by this time.

A test identical to that described above was conducted at the same time to demonstrate the concept of passenger protection by surrounding the passenger compartment with a fire-retardant shell that would protect the occupants long enough for the fire to burn out or for firefighting equipment to reach the airplane and extinguish the fire.

An airplane fuselage (actually one-half of the C-47 mentioned above) was fitted with a lightweight polyisocyanurate foam and an intumescent paint and tested in the JP-4 fuel fire mentioned previously. Temperature in the protected cabin changed very little for the first 6 minutes; but, as the heat finally penetrated, the temperature rose faster, reaching 300°F (149°C) as the fire burned out in 12 minutes. This temperature is within the human tolerance level (for more severe conditions) and indicated that, if temperature were the only consideration, passengers could have survived for this period.

Generation of toxic gases is as important a consideration as temperature. Up to 5 minutes into the latter test, no toxic gases were detected in the protected cabin. Unfortunately, at that point, the gas-sampling probe had to be withdrawn; therefore, no measurements were made later in the test. Although gas generation was a possibility later in the test, the amount of toxic gases was not believed to have been sufficiently high to have influenced survivability.

Had the test represented an actual airliner crash fire at an airport, firefighting equipment generally could have reached the airplane and extinguished the fire in less than 8 minutes. At the 8-minute elapsed time point in the test, there was no question of either heat or toxic gases endangering life in the cabin.

While the concept of passenger protection was adequately demonstrated by this test, it must be retarded as only the first step in developing an effective system to increase the chances for crash-fire survival. Many technical problems such as portection against fusealge rupture, providing protection for windows, and design problems associated with maintenance and operation* must be solved before such a sysrem can be used. Nevertheless, results of the test give promise that through proper design and use of suitable materials, protection may be provided for passengers caught in a crash fire.

3.2.4 In-Flight Fire in Unoccupied Lavatory

3.2.4.1 Description

A transatlantic commercial jet transport was nearing the end of its flight and was approximately 30 minutes from its landing destination when a fire was reported in the lavatory. An unidentified passenger left his seat, proceeded to the rear of the plane, and entered the closed lavatory where he encountered a wave of white smoke. He quickly closed the lavatory door and called for attendants.

The first steward went into the cockpit and reported smoke and fire in the aft lavatory. The cabin crew discharged two fire extinguishers inside the lavatory; but the smoke increased and became darker.

The captain radioed about the fire and requested emergency descent. At the same time he ordered the cabin depressurized and sent the flight engineer back to analyze the situation. The flight engineer proceeded to the rear of the cabin taking with him a CO_2 fire extinguisher bottle. Arriving in the back, the flight engineer saw the black smoke already completely filling the area behind the last row of seats. He handed the extinguisher to a steward and quickly proceeded back to the cockpit to report to the captain. As the airplane was descending the flight engineer proceeded to increase the airflow to the cabin and keep the smoke in the rear of the airplane.

Soon thereafter a steward came into the cockpit reporting that the passenger cabin was half filled with smoke and passengers were being affected. The captain ordered an overwing emergency window removed. A steward equipped with an O_2 bottle and a full face mask tried unsuccessfully to comply with that order.

Approximately 3 minutes after the first report of smoke and fire in the lavatory, smoke reached the cockpit and immediately filled it reducing visibility inside so that the pilots could not see either the instruments or outside through the windshield. Both pilots opened their sliding windows and the flight continued. Visibility was made possible through the open windows.

*For example, weight of foam, possible cracking and settling of foam from vibration, interference with fatigue analyses (G. P. Bates, Jr., private communication).

The captain decided to land as soon as possible and the aircraft was landed soon thereafter on an open field. During the landing both main landing gears broke off. The fu selage came to rest practically intact. After the aircraft came to rest, the fire, already in existence inside the fuselage, finally broke out on the top of the fuselage in front of the vertical fin. This fire consumed virtually the entire fuselage interior. Only one passenger and some crew members survived.

3.2.4.2 Analysis

This situation, an in-flight fire in an unattended area, poses a significant threat to human and structural survivability. Generally, access to such compartments is limited and hand extinguishment systems, if available, are not sufficient to suppress the fire. Detection of the fire is usually accomplished by either passengers or crew reporting smoke and noxious fumes in the cabin or cockpit. Detection may occur long after ignition of the initial fuel element and only after the fire has grown to in-flight uncontrollable proportions. Thyonly means of survival is to land the aircraft quickly, preferably at a location where ground firefighting equipment is available, but as indicated by the scenario, this is not always possible.

In the lavatory fire described above, no flames were evident inside the fuselage. The smoke pattern was as follows: white at the very beginning, then becoming darker, and then black and dense; the odor was not identifiable but very disagreeable and irritating to the eyes. Smoke progressed towards the front of the cabin from the ceiling to the floor. Survivors reportedly used portable O_2 masks. The fire appeared to have started in the concealed space behind the paneling in the lavatory.

Unfortunately, it is not known whether application of the fire extinguishers on board to the source of the fire might have extinguished it at this point. However, without further means of fighting the fire on board the crew elected to emergency crash land the pland and evacuate the passengers. Despite the crew's attempts, the combination of hazards including the lack of oxygen and presence of fire and noxious gases resulted in the death of the passengers aboard.

In such tragedies, the question always asked is: How might it have been avoided? The following recommendations are directed towards minimizing the hazard of in-flight fires in unattended areas:

1. Specific design changes and material selection should be made to minimize the rate of growth of fires and the evolution of smoke and toxic gases.*

2. An effective fire detection system should be developed that includes the elements of remote sampling (to provide an indication that a hazardous condition exists) and point sampling (to localize the danger).

3. A determination of optimum fire extinguisher systems should be made.

4. Specific data should be furnished to enable flight crews to identify smoke sources.

5. Procedures to control and exhaust smoke effectively during probable spe-

*The FAA issued a Notice of Proposed Rule Making in this area in the spring of 1975.

cific flight regimes while maintaining an adequate life support system should be established. Present "drop-down" emergency oxygen systems were designed and are effective only for depressurization use and not for use in a smoke and toxic gas environment.

3.3 Guidelines for Developing Aircraft Fire Scenarios

3.3.1 Introduction

Aircraft fire scenarios should be based on real incidents, either major aircraft fires and/or plausible extrapolations from minor incidents where proper design or timely interdiction prevented a major catstrophe. While most aircraft fire investigations are handicapped by the absence of trained observers during the active stages of the fire and by the extensive destruction of physical evidence, major accidents are thoroughly investigated by skilled investigators and the probable sequence of events frequently can be reconstructed with a high degree of confidence. In some cases, experimental simulation of critical elements in the scenario may be helpful in choosing alternative paths of fire development or in lending support to speculative deductions. In such cases, the fire scenario provides essential guidance for the design of meaningful experiments.

A practical range of fire scenarios can describe only a small fraction of fire incidents that could possibly occur in aircraft; therefore, it is necessary that they treat relevant factors that affect fire development in a way that permits generalization. In particular, scenarios based on real incidents will be retrospective in nature and will be incapable of predicting the effects of new designs and new materials on fire safety unless the teachings of the scenario can be applied to new situations.

This section is concerned primarily with the important physical aspects of an aircraft fire that belong in a scenario. In keeping with the focus of the study (i.e., on modifying materials to achieve fire safety), the physical behavior of fire is emphasized and the behavior of human beings is deemphasized. Nevertheless, it is obvious that people may enter into the fire scenario by: (1) preventing the fire, (2) starting the fire, (3) detecting the fire, (4) extinguishing the fire, (5) escaping from the fire, or (6) being killed or injured by the fire. However, the human psychological and physiological characteristics involved are beyond the scope of this report.

3.3.2 Ignition Source

In general, the fire scenario will start with ignition which may be characterized as the bringing together of an energy source and a combustible material in the presence of an oxidizing atmosphere so that a self-sustaining exothermic reaction occurs. Most atmospheres that support himan life also will support combustion so the presence of an ignition-supporting atmosphere may be taken as a "given" in aircraft fires and attention can be focused on the combustible material and the energy source. However, it must be recognized that local oxygen concentrations higher than in normal air (20.9 percent) may be associated with the oxygen supply

system and these higher concentrations can increase the susceptibility to ignition and the rate of burning of most combustibles.

Ignition sources in aircraft fires may be external to the aircraft cabin (e.g., lightning, hostile action, or failure of the fuel or propulsion system) or within the cabin (i.e., due to failure of operating equipment such as the electrical system, or the actions of passengers or crew, such as careless handling of smoking materials. In cabins ignitions are more amenable to control through proper materials selection than are the more catastrophic events of external ignition.

It would be desirable to have enough information about the ignition source to characterize it quantitatively. The primary characteristics of the ignition source are:

Maximum temperature (°C)
Energy release rate (cal/sec or watts)
Time of application to target (sec)
Area of contact (cm^2)

Considering the ignition source in terms of these parameters, it is possible to predict the response of the aircraft system to equivalent ignition sources of different origin. For example, a smoldering cigarette may be similar in terms of these basic ignition properties of an overheated electrical connection while a match will have characteristics more closely resembling those of a lighter. In this way, it is possible to generalize from a particular incident to a consideration of the probable effects of a range of potential ignition sources.

It will also be desirable to know the mode of heat transfer, which may involve some combination of conduction, convection and radiation, from the energy source to the target. Degree of air motion or confinement will affect heat transfer and, as already noted, access to adequate oxygen is a necessary condition for ignition. Preheating by prolonged exposure to a low-temperature energy source, such as a heating duct or overhead electric wiring, may make the target fuel more susceptible to ignition.

The most important single fact to recognize about a potential ignition source is that, for solid targets that are not readily ignitable, a "strong" ignition source generally will ignite the target while a "weak" one will not. The "strength" of the source depends on energy flux and time of application to the target or on the product of these two.

3.3.3 First Material Ignited

Identification of the first material to be ignited by the ignition energy source is a critical element in the aircraft fire scenario. This first step in the fire chain represents a transition from a controlled or transient energy release to an uncontrolled chemical reaction of combustible fuel and oxygen that is capable, if not checked, or accelerated growth to catastrophic proportion. Obviously, a favorable point at which to break the fire development chain is at the point of transition to active combustion. Of principal importance is an assessment of how the probability

of ignition, given exposure to an energy source, depends on the chemical and physical properties of the target fuel and therefore, a detailed description of the relevant target material properties is vital to the scenario.

Most organic materials, gases, liquids, and solids will ignite if brought to a sufficiently high temperature in the presence of an adequate oxygen supply. Combustible gas mixtures are more easily ignited and therefore should not be permitted in aircraft interiors. Many flammable liquids also are ignited easily and should be excluded. Aircraft fuels and other functional fluids essential to aircraft operation present an unavoidable ignition hazard, but this hazard will be external to occupied areas except in the case of catastrophic failure.

Solid combustibles probably will be the first materials ignited in aircraft interiors. These combustibles may be part of the aircraft structure, decorations, furnishings, or personal items brought aboard by passengers and crew. They may be derived from natural products such as wood, cotton, paper, and wool or synthetic plastics that appear in a great variety of compositions. Ease of ignition will depend on both the chemical composition and physical form of the material.

Generic terms such as polystyrene and polyurethane are inadequate to establish the chemical composition of a material since a great variety of additives (e. g., plasticizers, fillers, stabilizers, colorants, and flame retardants) that can affect ignitability may be added to the base polymer. Thus, it is desirable to obtain samples of the materials from the fire scene. If this is not possible, samples may be obtainable from other similarly equipped aircraft. The supplier's product designation and specification also should form part of the scenario data base.

Thermal properties of the target material play a vital role in determining ease of ignition. Since the ignition of a solid requires raising the temperature of its surface to some critical value (the "ignition temperature"), heat conduction* from the exposed surface of the interior will affect the time of ignition. This heat transfer mechanism obviously becomes crucial to a scenario if the heat flux is of relatively short duration, compared to the "ignition time." Elements made of materials with a large surface-to-volume ratio (e. g., wood or solid plastics) are slower to ignite since "ignition temperature" is reached later because energy is conducted from the surface to the interior.

In the case of composite structures, properties of the underlying layers also will affect ease of ignition. Thus, a thin decorative laminate may be difficult to ignite when bonded to the surface of an aluminum plate having a high thermal conductivity, but may ignite readily when placed on a plastic foam backing. Similarly, a carpet placed over an insulating underlayment will be easier to ignite than the same carpet placed directly on a solid floor.

Configuration of the material also can be of great importance in determining ease of ignition. Ignition tends to occur more readily in a crevice or fold or at an

*The material property parameter is "thermal diffusivity" which is the thermal conductivity divided by the product of density and specific heat. (G. R. Bates, Jr) – Private communication.

edge or corner than on a flat surface because of more effective heat transfer and heat conservation. Similarly, a vertical or downward-facing surface will be more readily ignited than an upward-facing one because of increased heat transfer from a rising convective heat plume.

It is apparent that a detailed description of the physical and chemical characteristics of the first material ignited is important to the first scenario to permit generalization from a specific case and prediction of ignition behavior in other situations.

3.3.4 Smoldering Versus Flaming Combustion

Some combustible materials burn in either a smoldering or a flaming mode. In general, only solids with very low thermal conductivity (e. g., fiber pad or plastic foam) can smolder. The ignition source may determine whether a material burns in the smoldering or flaming mode. A high-temperature ignition source, such as an open flame, will favor flaming combustion while a low-temperature source applied for a longer time, such as an overheated wire or glowing cigarette, will likely lead to smoldering combustion. A restricted air supply, as in a closed receptacle or compartment or the interior of a partition, also will favor smoldering combustion.

Smoldering combustion is characterized by the production of smoke and gas, a relatively low temperature, the absence of visible flame, and a slow spread rate. An upholstered seat cushion may smolder for an hour or longer and then burst into open flaming combustion. Smoldering combustion is important in aircraft fires because:

1. It may originate in relatively inaccessible locations and go undetected for relatively long periods of time, only to break out at some critical time such as when the aircraft is in flight of left unattended on the ground.

2. Gases produced are toxic to the occupants and may incapacitate the flight crew.

3. A transition to flaming combustion after a long period of smoldering may produce a very rapid growing fire because of the preheating of fuels and accumulation of combustible gases during the smoldering period.

4. Smoke and gas produced provide a possible means of early detection through the use of suitable detectors.

5. Smoldering fires appear to be very difficult to extinguish (a gaseous extinguishing agent such as carbon dioxide or a halon* may extinguish flames but smoldering combustion may continue (deep seated fire) and the flame might rekindle after the extinguishant has dissipated).

*Halon: a generic name for several halogenated hydrocarbon compounds used as fire extinguishing agents (Keivshinoff, Fristron and True, *Fire Sciences Dictionary and Source Book,* Applied Physics Laboratory, Johns Hopkins University, 1974, p. 114.

Flaming combustion is characterized by visible flames, high temperatures, and rapid growth if unchecked. Its presence usually does not go long undetected, and the issue of control of the fire or catastrophic failure is quickly decided.

Thus, smoldering combustion is a more insidious hazard. The possibility of its occurrence should be carefully considered in investigating accidents or constructing scenarios.

3.3.5 Fire Spread

After ignition, the future course of a fire will be determined by the rate of fire growth and the time at which various defensive actions are brought into play; therefore these factors are critical elements in the aircraft fire scenario. A small fire, discovered at an early stage, may be controlled by improvised methods readily at hand. If it has time to grow, a portable fire extinguisher may be necessary. At a still later stage, a fixed on-board extinguishment system may be able to control the fire. In the case of fires on the ground, auxiliary ground-based firefighting equipment may be able to cope with still larger fires. If the rate of fire growth outpaces the speed with which defensive measures can be brought into action, catastrophic failure will occur.

Fire growth in an aircraft may be characterized in different ways, depending on the nature of the fire. In a smoldering fire, it may be measured by the rate of accumulation of snoke and other combustion or pyrolytic products. In the case of open flaming, the rate of energy release leading to intolerably high temperatures, or the rate of destruction of operating systems leading to loss of control of the aircraft may be critical. In a ground fire, the rate of destruction of property may be a more appropriate measure of fire spread rate.

Fires grow by spreading over the surface of a locally ignited fuel element or by jumping from one fuel element to the next. The process may be viewed as one of successive ignition or new combustible fuel surface elements ahead of the advancing fire; therefore, most of the material characteristics that affect ease of ignition will affect rate of flame spread in similar ways. Combustible materials with high surface-to-volume ratios and low loss of heat to some thermal sink will spread a fire rapidly. Gaps between fuel elements will slow or stop the spread of a fire rapidly. Gaps between fuel elements will favor rapid fire spread. Melting, dripping, and flowing of thermoplastic materials and structural collapse may contribute mechanically to spread of fire. On the other hand, melting of a thermoplastic may remove flammable material from the ignition source before ignition.

As the size of a fire increases, radiative and convective heat transfer increases and orientation effects become increasinglv important. Fires spread more rapidly in an upward direction and more slowly in a horizontal or downward direction. Thus, the upper part of a compartment will become involved in a fire early while the floor and lower regions may not contribute until later stages.

A growing fire will consume large quantities of oxygen from the air. In a tightly-closed compartment such as an aircraft cabin, the rate of fire growth may be

limited by the available air supply (ventilation limited fire). Factors that increase the ventilation rate, such as forced ventilation, breaking of windows as a result of the fire, rupture of the fuselage, or deliberate creation of openings in the course of escape or firefighting activities, will increase the rate of fire spread. Increased oxygen concentrations from an oxygen supply system will produce high temperatures and rapid fire spread.

In the later stages of a compartment fire, all of the fuel surfaces (i. e., surfaces of combustible structural materials) will become heated by radiation from the smoke and flame and from the heated ceiling and upper walls. As these surfaces approach their ignition temperatures, flame spread accelerates very rapidly and the entire compartment becomes engulfed in flames (a phenomenon referred to as "flashover"). At this point, human survival within the compartment becomes impossible; internal firefighting efforts are largely ineffective.

Under conditions of limited ventilation, combustible gases produced by pyrolysis may accumulate within a compartment. If these gases are mixed with a fresh air supply, for example, by rupture of the fuselage in a crash landing, a very rapid anddestructive fire (flash fire) can result and will quickly engulf the whole aircraft.

3.3.6 Evolution of Smoke and Toxic Gases

In a building fire, smoke and toxic gases may spread from the region of active burning and produce casualties as well as property damage in areas remote from the point of origin. Such long-range effects are less important in the more restricted environment of an aircraft interior where an uncontrolled fire will quickly render the entire interior uninhabitable. Nevertheless, smoke and gas evolution may be important in aircraft fire scenarios for the following reasons:

1. Smoke and fire gases may provide the first warning of a developing fire. The human nose is a very sensitive detector, and highly sensitive mechanical detectors are available for use in uninhabited or inaccessible spaces.

2. The gradual accumulation of combustion products from a smoldering fire in the confined interior of an aircraft can affect the occupants by causing confusion, panic, incapacitation, and death. Incapacitation of the air crew in flight would lead to complete failure of the man-machine system. An on-board (independent of cabin atmosphere) oxygen supply system and smoke masks for personnel, as required by present regulations, may permit continued operation for a considerable time in the presence of a smoldering smoke and gas source if the protective equipment were used.

3. Combustible gases can accumulate in confined spaces to form a combustible gas mixture with air. If this mixture is ignited (e. g., by an electrical spark), a very rapid (possibly explosive) and destructive fire (flash fire) can result.

4. Post-crash fires may produce a condition of flaming exposure leading to rapid generation and/or accumulation of smoke and toxic gases.

3.3.7 Detection

The first detection of a fire is a critical event in an aircraft fire scenario since it determines the type of defensive action that may be possible and the probability of success. Detection may be by the passengers or crew of the aircraft or, in uninhabited spaces, by instruments. Detectors may be sensitive to heat or to the gaseous or particulate products of combustion. The latter are much more sensitive and have shorter response times than the former, but they also are more prone to false alarms and, therefore, have been less used in aircraft than the heat-sensitive types.

Because of the low temperature and localized heat output, smoldering combustion may escape early detection by a thermal detector. Smoke and gas may give warning of smoldering, but location of the source may be difficult if the fire occurs within partitions or structural elements since the smoke may appear some distance from the actual fire. The location of the fire detectors is very important in the early detection of aircraft fires since ventilation patterns and compartmentation can affect the flow of heat and combustion products from the source to the detector.

3.3.8 Extinguishment

The role of extinguishment in the aircraft fire scenario will depend largely on the state and location of the fire when discovered and on the meansof extinguishment available. A small fire in the open may be extinguished by impromptu means (e.g., burning newspaper can be extinguished by smothering with a coat or blanket). A somewhat larger fire may be controlled using a portable fire extinguisher, usually operated by a trained crew member. Smoldering combustion may be more difficult to control because it may originate in less accessible locations and because deep-seated combustion does not respond to the surface application of extinguishment systems activated automatically by fire detectors. These systems usually are used in nonoccupied locations. Finally, ground based firefighting equipment may be available to deal with crash or ramp fires.

Means of extinguishment for use on board an aircraft are limited by: (1) space and weight considerations; (2) the need for the aircraft to remain operational after the fire emergency has passed; and (3) the frequent impossibility of immediate evacuation. Water, the traditional extinguishing agent, generally is not suitable for on-board use. Gaseous extinguishing agents, either inert dilutents such as carbon dioxide or agents such as certaihalogenated hydrocarbons (Halons*) are used in small portable and fixed systems. Halons are more efficient than carbon dioxide, but they decompose in a hot fire to give off toxic and corrosive products. Halons themselves are slightly toxic to humans susceptible to heart problems or over extended periods of exposure. Interactions between human occupants and the fire extinguishing system may be an important part of a fire scenario.

*See footnote on p. 27.

3.3.9 Essential Scenario Elements

The aircraft fire scenario, whether intended to recreate the details of an actual incident or to describe hypothetical events as a tool for design safety analysis, describes significant factors and events in the development of the fire from ignition to successful control or catastrophic failure. As many as possible of the following points should be covered.

1. The source of the ignition energy should be identified and described in quantitative terms.
2. The first material ignited should be identified and characterized as to chemical and physical properties.
3. Other fuel materials that play a significant role in the growth of the fire should be identified and described.
4. The path and mechanism of fire growth should be determined; particular attention should be given to fuel element location and orientation, ventilation, compartmentation, and other factors that affect fire spread.
5. The possible role of smoke and toxic gases in detection, fire spread, and casualty production should be determined.
6. The possibility of smoldering combustion as a factor in the fire incident should be considered.
7. The means of detection, time of detection, and the state of the fire at the time of detection should be described.
8. Defensive actions should be noted and their effects on the fire, on the occupants, and on aircraft operation should be described.
9. Interactions between the occupants of the aircraft and the fire should be detailed.
10. The time and sequence of events, from the first occurrence of the ignition energy flux to the final resolution of the fire incident, should be established.

In addition, the scenario should permit generalization from the particular incident described and should provide the basis for exploration of alternative paths of fire initiation and as well as for analysis of the effect of changes in materials, design, and operating procedures on fire safety performance. When used in this way, the fire scenario can be an effective tool in increasing the fire safety of aircraft by increasing man's capability to visualize and comprehend the events.

3.4 Guidelines for Analysis of Fire Scenarios in Aircraft

3.4.1 General

Prevention and control are prime purposes of any fire scenario analysis. Fire scenarios may be, and whe possible should be, based on real fires. Developing a fire scenario requires either a completely documented report of a detailed post-accident investigation and analysis specifically designed to determine how and where the fire started and progressed until extinguishment or a similar report of an instrumented

full-scale test burn. In either case, until existing knowledge of dynamics of actual fires is augmented by fire dynamics research and studies, development of scenarios will be an art rather than a scientific presentation of irrefutable evidence. Nevertheless, full analysis of the most probable fire scenario is a necessary and effective tool for use in developing economical and realistic methods for preventing and controlling fire in aircraft.

3.4.2 Prevention

The elements of aircraft fire scenario analysis that can contribute to prevention of fire involve the broad areas of education, aircraft design (including choice of materials) and construction, regulations (legal, carrier, airport, or industry), and operating procedures. Complex interaction among and between these areas is obvious.

The scenario of an in-flight fire in an unattended area as presented in Section 3.2.2, will be used here solely for purposes of illustration and therefore due to abridgment may be technically imprecise for any other usage (see Section 3.2.2 for details).

3.4.2.1 Education

As one analyzes development of the in-flight fire, one must ask: How could it have been prevented or minimized? Who, without adequate understanding, allowed the fire to ignite or continue?

The failure of the battery, the alleged source of ignition requires: (1) identification of the actual failure mechanism, and (2) identification of interim and/or permanent means to assure that such batteries do not cause or contribute fuel to the subsequent aircraft fire. This remedial action could involve considering replacement, increased periodic inservice testing and inspection, better maintenance crew instruction, and other measures such as use of fire resistant battery enclosures and fire detection mechanisms.

To the fullest degree possible, representatives of all those who work in the aircraft industry should analyze fire scenarios to extract needed data on fire prevention and then use the data to prevent or minimize future fires.

3.4.2.2 Design

From the standpoint of aircraft design and construction, the factors that should guide the analysis of a scenario are the engineering factors related to materials choice and usage (see Section 3.4.2.2.1). In analyzing fire development, the principal questions focus on how the fire could have been prevented during the design and construction of the aircraft, what changes in design or construction procedures should be made, and how the knowledge gained from this fire should be applied to other existing aircraft and/or in the design of new aircraft. (Overall aircraft fire safety design considerations can be found in Chapter 4.)

The illustrative aircraft fire scenario (see Section 3.2.2) will be employed to consider the design of materials choice and arrangement.

3.4.2.2.1 Materials Choice and Arrangement

Consideration of materials in design comprises not only the materials chosen for the element – in the case of the illustrative scenario, a battery case – but also the geometry or shape of the element and its physical location in the overall layout of the aircraft. Here the greatest gain in fire prevention may be possible. Thus, one should ask: Could the batteries, which initially caused the fire, have been located elsewhere? Could a lightweight, strong, and fire-resistive ceiling in the electrical compartment have been designed to create a fire-safe floor-ceiling envelope to protect vital elements such as the control rods, stringers, and the cabin floor? Could the battery case be designed of material more difficult to ignite? What fire tests are now applied to the batteries? Are the chosen end limits correct or does this fire suggest the need for more stringent end limits or perhaps a different test procedure? Could the battery be enclosed in a fire resistive tray enclosure? These and other basic design questions should be considered and practical solutions derived for the battery selection and installation arrangement on this as well as all aircraft.

3.4.2.3 Regulations

The term "regulation" as used in this report includes Federal Air Regulations (FAR) and Military Regulations (MR); the regulations (rules, design procedures, design practice) of air carrier operators, aircraft manufacturers, and material suppliers to carriers and manufacturers; and test methods and specifications as well as the standards incorporated or referenced therein. If one considers the impact of manufacturing quality control on mass-produced items and the effect of in-service inspection and maintenance, the importance of the regulations of the air industry is quite apparent.

Analysis of an aircraft fire scenario from the regulatory point of view would focus on two aspects: First, one must determine whether all applicable regulations have been adhered to in the design, construction, maintenance, and operation of the aircraft involved in the fire. If the regulations have essentially been complied with, the more difficult task begins. Second, one must consider where, how, and by whom the regulations should be amended or new regulations (tests, specifications) developed to prevent a repetition of the fire; whether an improvement in fire control provides an equal and/or more economical solution; and whether the fire hazard identified is unique to a particular use of a specific aircraft or to one model or type of aircraft or is essentially common to all aircraft.

In the illustrative scenario, the hazard of a thermal runaway in a battery may well be common to any aircraft using the specific type of battery. If this is accepted as essentially correct, change in the regulations regarding batteries and their installation, inspection, and maintenance could be the result of in-depth aircraft fire scenario analysis.

3.4.2.4 Operating Procedures

The term "operating procedures" as used in this report denotes procedures promulgated by any of the agencies mentioned in the above discussion of regulations. Included are: rules for the use, operation, maintenance, and inspection of components and aircraft systems as well as all types of "checklists," the established way for handling routine, nonroutine, and emergency situations; and procedures for fighting or extinguishing fire and for removal of humans endangered by fire.

In analysis of an aircraft fire scenario, procedures related to fire safety are of prime concern. Here again, one first must attempt to determine, from the scenario analysis and investigation report, that existing operating procedures were followed. If such procedures were followed, one must reanalyze the fire scenario from ignition source to extinguishment asking, at each main action point, how operating procedures could be modified to prevent fire or fire progression at this point and/or to reduce loss of life, injury, or aircraft damage.

3.4.2.4 Summary of Guidelines for Analysis of Aircraft Fire Scenarios from the Fire Prevention Viewpoint

Fire is a complex problem involving not only what is done but also what is not done; consequently fire prevention is also complex. Improvement in fire prevention is technically, economically, and socially feasible now. There is no need to wait for more basic research or better tools or test methods; rather, use of current resources must be maximized with competent people being of primary importance.

The foregoing discussion has been presented to show how a multifaceted and multidisciplinary systems analysis of aircraft fire scenarios may be accomplished; it has been deliberately broad and somewhat elementary. An actual systems analysis of real aircraft fire scenario is quite specific and can be elementary or technically sophisticated in its findings.

As the use of polymeric materials in aircraft increases, the total impact of these materials on the degree of hazard present must be both assessed and controlled. In this regard, comprehensive aircraft fire scenario analysis is an effective tool.

3.4.3 Control

The elements of fire scenario analysis that can contribute to control of aircraft fire involve the broad areas of detection, containment, life support, extinguishment and egress. A definite relationship exists between these areas and those covered in the above discussion of prevention, therefore, some overlap exists in the discussion (indeed, the guidelines that must be kept in mind relative to control of aircraft fire during a scenario analysis warrant repetition). The scenario of the in-flight fire in an unattended area (Section 3.2.2) will be used to illustrate control considerations just as it was in the above discussion of prevention, and the reader is reminded of the technical limitations of using the scenario in this way.

As the fire scenario is analyzed with regard to each of the broad areas enumerated above, the basic question to be asked at each main action point is: What could have stopped the fire, minimized its progress, or protected life at this point?

3.4.3.1 Detection

Detection, human or mechanical, alerts individuals to the possible presence of a fire. The guiding factor for the analysis of aircraft fire control from the detection aspect are those related to the use of human senses or mechanical devices to identify the existence of a fire threat and, thereby, lead to initiation of control action. The value of detection in control of fire is directly related to the time which elapses between ignition and detection.

3.4.3.1.1 Human Detection

Human detection and the response that detection generates is a prime fire control factor. Human detection involves several elements including the deliberate or accidental actions that lead to human sensation (sight, smell, sound or touch) warning that fire may exist and the trained or instinctive responses of the person receiving the initial warning. One cannot forget the responses of those subsequently becoming aware of the possible or actual existence of a fire condition.

In the illustrative scenario, human detection functioned as part of aircraft fire control as described below. Smoke was observed by a cabin attendant, and this was the accident observation or detection of fire that triggered a trained response. The aircraft commander was notified, the presence of smoke verified, and deplaning procedures initiated to assure passenger safety.

In addition, the investigation report noted that during landing roll-out, 3½ minutes before the presence of fire was verified and emergency procedures started, the captain noticed an unusual odor, and he and the first officer decided that the odor was caused by engine fumes drawn into the aircraft through the fresh air inlet. It is at this point in the analysis that some questions arise: Should the captain, during a landing roll-out, have ordered his first officer or cabin attendant to take a walk through the aircraft to check for smoke or fire? Would such a request have been prudent, overcautious, or even dangerous during roll-out and taxi operations? Was having the first officer verify the attendant's report of cabin smoke wise or wasteful of time? Do either of these factors suggest change in operating procedure when a flight crew member believes he has detected the presence of fire aboard the aircraft?

As indicated above, human detection can be deliberate or accidental and can invoke a trained or instinctive response. With regard to aircraft, it is suggested that effective control of fire would support a deliberate and conscious effort on the part of all air and ground carrier personnel, airport personnel, and federal personnel involved in air operations to detect fire and/or smoke. These personnel should be

trained* to: recognize the kind of fire (e. g., electrical), know the types of extinguishers available (hand and built-in), how and when to use them, and how to control a crowd under conditions of limited or no egress (panic on an aircraft might be more dangerous than the fire).

Standard procedures should be established for fires occuring in various parts or compartments of aircraft during the phases of operations (i.e., consideration should be given to electrical fires, baggage fires, galley fires, passenger compartment fires, fires in fuselage walls, etc., during phases of operation such as hangar maintenance, ramp operations, taxiing, take-off, in-flight and landing). In this regard, training should include actual fire experience under controlled conditions. Periodic refresher training and testing such as that now used to assure pilot proficiency should be initiated and/or expanded.

These efforts would maximize early trained human detection and responses to fire, thus enhancing the possibility that subsequent control activities will be successful. Particularly important is that passenger control, a vital element in commercial operations, would be maximized by the firm and confident attitude that well-trained professionals project to others at times of extreme stress; the danger of panic that might result from an accidental and untrained instinctive response to fire would be minimized.

3.4.3.1.2 Mechanical Detection

Three basic types of instrumented fire detection devices are presently available; the photoelectric type, the ionization type, and the gas detector type. Each is designated to measure one or more of the early products of combustion.

To prevent or better control future aircraft fires, full aircraft fire scenario analysis should note detector usage and consider it in the recommendation developed as a result of the analysis. The major concerns in scenario analysis are whether a detection device was present near the ignition point and, if so, its type (the products of combustion are measured) and performance (whether it was functioning properly). If detectors were present, one also must consider how far the scenario would progress before the alarm was given; whether the activated alarm would utilize a noise, a panel indication, or both; where in the aircraft the alarm would register; how precisely it would pinpoint the fire location; how reliable the system is; and whether frequent false alarms may have dulled human response. If detectors were not present, the analysis should consider the implications of this deficiency at each main action point of the scenario and clearly state the cost in lives, suffering, and damage of not detecting the fire at the earliest practical time.

Further insights into the question of detection devices can be gained by considering the possible results of the illustrative scenario fire had it occurred in the aircraft on a worst case basis. For example, what would have happened if the electrical fire had occurred at an over-water point of no return on a maximum range

*It should be recognized that airlines generally try to operate good training programs; however, better training is always useful.

flight for the aircraft in question? It should be noted that there was no mention of presence of a detector in the electrical compartment and that *Airworthiness Directives* do not require such detectors in this sealed compartment of the aircraft. Thus, detection of any fire must be by human detection.

3.4.3.2 Containment

The factors that guide the analysis of an aircraft fire scenario with respect to fire control through containment are those related to use of active or passive containment measures – i.e., mechanisms used to stop growth or spread of a fire, minimize its progress, or facilitate extinguishment. An active mechanism is one that is activated automatically or manually after detection of a fire to contain and/or extinguish the fire. A passive mechanism is one that either is an integral part of the component or system subject to fire attack or is activated by the fire to contain, limit, and/or extinguish the fire.

As the aircraft scenario is analyzed, a number of questions should be considered: What active or passive containment mechanisms were present? Did they function as designed? Were they effective? Would different or additional active or passive containment measures significantly alter the aircraft's response to this fire and to fire in general? What knowledge, with regard to containment, can be generalized an; applied effectively to other existing or planned aircraft?

The test methods used to evaluate the active or passive containment mechanisms incorporated into the aircraft also should be considered in the scenario analysis to determine whether the mechanisms reacted to the real fire in the manner predicted by the acceptance test methods and whether changes in the test methods or accepted criteria are included. One also must assess the import of aircraft design and materials on containment of the fire (i.e., whether they contributed or prevented the contribution of added fuel or gaseous products to the fire).

Analysis of the containment reponse of the aircraft or an aircraft compartment is the most complex portion of the scenario analysis and much needed knowledge of the actual fire dynamics frequently will not be available. Mathematical or analytical models, based on prior research, quantitative and qualitative tests, materials characterization, and systems analyses may have to be developed and integrated with the scenario information. Human factors also must be considered since often a human must respond to detection and provide or activate an active containment mechanism.

3.4.3.2.1 Active Containment

In the illustrative scenario, the initial active containment "shutting down" mechanism was the request to the Air Traffic Ground Controller for a smoke check and then subsequent announcement and request for airport firefighters and equipment, which provided the rest of the active containment measures. Involved in containing the fire were pieces of equipment dispensing 165 gallons of liquid foam,

1,500 pounds of CO_2 and 3,600 gallons of water. The ignitor, the battery was removed from the aircraft during the final phase of fire control approximately 10 minutes after smoke was first detected on the aircraft.

Absence of active containment mechanisms in the electrical compartment would be an area of concentration in the aircraft fire scenario analysis. The findings with regard to this compartment during analysis of all the other aspects of scenario analysis should be integrated at this point, and a firm case for measures that would have prevented or controlled the fire should be developed. The analysis should take into account not only ignition due to thermal runaway of a battery but also any other probable source of ignition in this compartment. A means of actively contain *all* probable fires should result from the analysis.

3.4.3.2.2 Passive Containment

In the illustrative scenario, the major elements in the compartment that require consideration from the standpoint of passive containment are the control push rods, floor support stringers, and floor assembly separating the electrical compartment from the passenger cabin. The analysis should focus on design criteria, materials, test methods, and acceptance criteria used for the control push rods. Some factors to consider are whether these vital control rods could be located within a more fire-resistive envelope, the degree of fire endurance the rods and related assembly should have, whether the materials used in the rods are acceptable when one considers the probable fires in the electrical compartment or other compartments the rods pass through; whether the fire tests used reflect the severity of the most probable fire, whether the fire test acceptance limits are adequate, and whether other or additional fire tests should be used.

The analysis of the floor stringers and floor assembly should focus on the system that these structural elements create and establish the degree of fire resistance and fire endurance the system should be able to endure without failing structurally or permitting the passage of flame or hot gases to the passenger cabin. The design criteria for the stringers and floor assembly then should be reviewed to determine whether or not the required degree of fire resistance and fire endurance is obtained. Finally, necessary changes in design, materials, test methods, and acceptance criteria should be described in terms of cost effectiveness. Knowledge of design mechanisms, test methods, and construction specifications currently used in the building industry may provide a useful input, and use of building industry engineering analysis methods may prove helpful because of the criticality of weight on all aircraft.

3.4.3.3 Life Support

The life support factors that guide analysis of aircraft fire scenarios with respect to fire control are those related to the use of active or passive means to support and prolong life aboard an aircraft during fire. A direct relationship exists

between life support and extinguishment and escape since, once a fire begins, the life support system must sustain life until the fire is extinguished or until escape, assisted or unassisted, is possible.

Active measures are those actions taken directly by occupants of the aircraft to maintain life and include mechanisms and devices automatically or manually activated to provide life support until extinguishment or escape can occur. Materials of construction are most important in analyzing life support systems; unfortunately, some of the materials used in the chemical generating system examined by the committee are not the best choices from a fire safety point of view. The hazards posed by some of the polymers used in life support systems make analysis of their behavior imperative. Other aspects of active life support systems that require consideration are illustrated by the scenario (Section 3.2.4) of an in-flight fire in an unoccupied lavatory. In this scenario, the flight crew elected to shut off oxygen to the passenger section, probably to minimize the hazard of free oxygen. Shortly thereafter, the passengers were dead or incapacitated due to smoke and noxious (possibly toxic) gases generated by the fire. Analysis of this facet of the scenario prompts the questions: Should the oxygen supply have been shut off? If not, what operational procedure should the crew have followed? Do modern aircraft contain a life support system that can sustain life under these conditions without enhancing the growth and propagation of the fire? Current requirements, criteria, test methods, hardware, operating procedures, and regulations should be analyzed in light of this scenario.

Passive life support measures involve the ability of the life support system to respond to the fire situation. Referring again to the in-flight lavatory fire scenario, it is indicated that two passive measures failed to support life and both involved the passage of smoke and noxious gases. The initial failure involved the passage of smoke from the lavatory on fire to the other lavatory which led to attempts to extinguish a fire in the wrong place. The second failure was the smoke chute, which did not provide a means to contain smoke emanating from the cabin or cargo area or to prevent such fumes from entering the cockpit. This situation contributed to the decision to crash land and to shut off the oxygen to the passenger section. Analysis of hypothetical fire scenarios during the design stage might have identified these problems and prompted changes that would have saved lives.

Life support systems, for the most part, are created during the design of an aircraft. The fire scenarios under which the system functions must be explored. Extensive use of polymers in the modern aircraft industry make such analysis even more important. Thus, the industry and government should cooperate in the design of hypothetical fire scenarios that can be used to guide and direct design. Ultimately, such recommendation scenarios should be based on instrumented full-scale fire simulation experiments.

3.4.3.4 Extinguishment

Guidelines for analysis of aircraft fire scenarios, with respect to fire control

through extinguishment, will be limited to extinguishment factors and equipment incorporated into the aircraft. Local firefighting equipment and methods will not be discussed beyond stating that such external extinguishment capability will not be available during the most critical period of most significant aircraft fires. Simply stated, the most critical period in an aircraft fire is that point at which the extinguishment capability on board the aircraft would not extinguish the fire.

The extinguishment factors for polymers used on board the aircraft, particularly for cabin interiors, are mainly passive mechanisms. They are activated by the fire and generally are integral to the component or system subject to fire attack. These mechanisms tend to extinguish the fire by containing it until fuel or oxygen depletion cause extinguishment or by reacting to the fire in a manner that facilitates extinguishment through thermal/chemical action. Char-forming elements, nonflammable materials, and intumescent coatings are examples of this latter mechanism.

The extinguishment equipment on board an aircraft comprises apparatus designed to fight and extinguish fire and devices or items that can be pressed into such service in an emergency. Fire extinguishers represent an active category of equipment, whereas pillows or briefcases that can be used to smother a small fire in a trash receptacle are examples of passive items.

As the aircraft fire scenario is analyzed, a number of questions should be given attention: What active or passive extinguishment equipment or factors were present? Did they comply with applicable regulations? Was the equipment used properly? Did it function as designed? How effectively? Did the extinguishment factors respond? How effectively? What difference or additional extinguishment equipment or factors would be needed to have significantly altered the fire scenario? How would such changes alter other fire scenarios anticipated for this aircraft? Can the knowledge gained from this scenario analysis be generalized and applied effectively to other existing or planned aircraft? Test methods used to evaluate and accept the extinguishment equipment as well as establish the extinguishing mechanisms integral to the aircraft materials and components also should be subjected to such analysis. Finally, the relationship between the extinguishment factors and equipment and the other elements of tne aircraft fire scenario should be integrated so that final recommendations derived from the analysis meet the technical, cost-effectiveness, and implementation criteria critical to effective engineering analysis of the overall problem area.

3.4.3.5 Escape

Analyses of aircraft fire scenarios should consider the effectiveness of built-in escape mechanisms, operating procedures, as well as attendant and crew actions under prevailing conditions (FAR 25.803 noted in Appendix C discusses the current emergency evacuation standards required under current Federal Aviation Administration regulations). Two factors to be determined at the outset are whether the aircraft's evacuation system, the crew's operating procedures, and attendant training complied with applicably standards.

If such a determination is substantially positive, it is important to know how evacuation proceeded under the conditions established by this fire scenario. Among the factors to be considered are the exits that were available and functional as well as the available paths to these exits; the location of cabin attendants and how they were able to implement the emergency procedures; the effect of materials choice and arrangement, containment, life support, extinguishment features and systems used on egress under the fire scenario conditions. Based on this analysis, it must be determined whether changes in the emergency evacuation system on the aircraft would result in more effective evacuation under the conditions present during the fire scenario, how such changes would impact on evacuation during other anticipated fire scenarios, whether the knowledge gained by this analysis can be generalized and effectively applied to other aircraft, whether change or modification of the Federal Air Regulations is warranted, and, if so, what changes could be implemented effectively.

3.5 Conclusions and Recommendations

Conclusion: Scenarios sufficiently detailed to allow optimum fire safety design of aircraft were not available to the committee. Furthermore, fire scenarios developed solely on the basis of accident investigations would be inadequate to achieve this objective. *Recommendation:* Generalized scenarios (as outlined in Section 3.3) should be developed on real or credible incidents. The specific events in these scenarios (e.g., rate of fire spread, heat release) should be further quantified by information obtained from large-scale experiments. The ultimate goal is to develop the capability of employing models to predict fire hazard and, thus, replace expensive large-scale experiments.

Conclusion: The application of fire scenario analysis to improve aircraft safety is the most productive methodology for dealing with the complex aircraft system. *Recommendation:* Scenarios should provide increased survivability. In particular, these scenarios should provide the basis for: (1) material selection, (2) design criteria, (3) validation of test methods, (4) promulgation of regulations, (5) personnel training, and (6) research and development objectives.

Conclusion: Information from actual aircraft fire incidents is incomplete and not readily available. In general, what information is available is insufficient to provide a basis for useful scenarios. The reason for this state of affairs is inadequate collection and reporting of field data. *Recommendation:* Accident investigation teams should utilize the general mode of scenario development presented in Section 3.3 to ensure that all the essential elements of the fire scenario are adequately addressed in their accident reports. In addition, the National Transportation Safety Board should (1) broaden its coverage to include minor and incipient fires, including those that do not cause injury or structural damage, and (2) promptly disseminate the information that it collects.

CHAPTER 4

THE AIRPLANE SYSTEM: EXAMINATION OF DESIGN FUNCTIONS AND MAN'S OPERATION

4.1 Introduction

Unlike most other forms of rapid mass transportation, the airplane is a completely self-contained unit. It provides all the mechanical resources and life support systems needed to properly and effectively perform its functions of safely and comfortably transporting people and/or cargo over prescribed distances with reasonable economy and virtually complete independence from other logistic and assistance sources.

In view of the nature and function of aircraft as well as the fire ignition sources and fire load levels present in the modern air vehicle, fire hazards and control capabilities must be defined. Thus, this chapter defines the three principal fire hazard modes for survivable incidents and discusses prefire initiation considerations, including determination of fire potential and current prevention and control systems.

4.2 Aircraft Fire Hazard Modes for Survivable Fire Situations

A survivable fire incident is defined as an accidental occurrence in which injuries received by passengers or crew members, not attributable to fire or its effects, are such that survival of all or most of those persons is probable. Three types of survivable fire situation are considered: the ramp fire, the in-flight fire, and the post-crash fire. Ramp fires usually involve empty aircraft and no loss of life, but are becoming a serious economic problem. Past history of aviation indicates that in-flight fires are usually controlled so that few fatalities o cur (however, see Section 4.2.2); the Hindenburg airship fire in 1937 and a fire on an aircraft approaching Paris in 1973 are the worst examples of in-flight fires resulting in fatalities. Fires following a crash however, are a serious problem.

4.2.1 Ramp Fires

The ramp fire involves attended or unattended parked aircraft. Personnel aboard could include flight crew, passengers, and ground maintenance personnel. The aircraft could be parked at a passenger loading ramp or a ground maintenance position or could still be under construction at a factory.

The causes of ramp fires involving commercial air carriers and military aircraft vary. Electrical system and servicing errors, during oxygen system changing, account for the majority of known ramp fires on worldwide U.S. air carriers while fueling procedures and engine fires account for the majority of military aircraft

ramp fires. A photograph of an unattended ramp fire in progress in the interior of an L-1011 at Logan Airport on Boston on April 20, 1974 is shown in Figure 1.

Analysis of data on ramp fire causes (see Appendix A) indicates that development of electrical malfunction monitoring devices and improved oxygen system servicing arrangements will produce improved ramp fire protection for commercial aircraft. In several instances, unattended ramp fires have progressed to the point at which the cabin was destroyed despite the availability of fully outfitted firefighting groups (e.g., UAL Boeing 720, Philadelphia, 1970; KLM Boeing 747, Amsterdam, 1972; TWA Lockheed L-1011, Boston, 1974). Attended ramp fires have been successfully put out with limited damage. Tests and experience indicate a high probability of passenger egress during ramp fires, provided the passengers have a protective shield between them and a fuel fire or no such fire exists. These data also indicate that if a fire is allowed to progress past a critical point, conventional firefighting methods are inadequate.

4.2.2 In-Flight Fires

In-flight fires can occur at any time during a flight and at any place where fuel and an ignition source are available. A number of in-flight fires, often in lavatory areas, have been passenger-initiated. A recent in-flight cabin interior fire on a Boeing 707-300 aircraft resulted in 124 fatalities and destruction of the aircraft after a successful (survivable) emergency crash landing (Figures 2 and 3). This fire did not involve the aircraft's engine fuel and was fed only by the cabin interior materials, passenger-servicing materials, and passenger carry-on materials.

Engines and fuel systems are the major causes of in-flight fires aboard military aircraft while the galley is the greatest source of in-flight fires on U.S. civil air carriers (many minor fires promptly extinguished by hand fire extinguishers have occurred in galley areas). The airplane propulsion system is the next most serious fire hazard and is the subject of much work by the entire aviation industry. Electrical malfunction and cigarette smoking are the next most frequent ignition sources in civil aviation. (A compilation of in-flight fire causes is presented in Appendix A).

Additional system effort, parallel to that directed toward engine and fuel systems, to fire harden galley (and the in-flight food service system) and lavatory areas, as well as the electrical system (this includes conveniences such as electric razor outlets), should improve aircraft safety. Further control or elimination of smoking in aircraft also would reduce the fire hazard.

4.2.3 Post-Crash Fires

The post-crash fire occurs after an aborted take-off or a crash landing. A survey of 535 worldwide commercial turbine-powered aircraft accidents between 1952 and 1971 revealed that fiιe did not occur in the majority of accidents but that there were at least 182 accidents in which fuel spillage and post-crash fire did occur. These accidents were caused by hard landing, gear-up landing, gear col-

Figure 1. Ramp fire in progress.

Figure 2. Post-landing-in-flight fire.

Figure 3. Post-landing-in-flight fire.

lapse, landing short, over-shooting the runway, and impacting into obstructions or terrain during takeoff, landing, or enroute. Of these 182 accidents, 60 were not impact survivable (1,953 fatalities). In the 122 accidents that were impact survivable to some degree, there were 1,015 fatalities and over 4,000 survivors. Thus, 23 percent of the worldwide accidents were impact survivable to some extent and resulted in post-crash fires. While it is not possible to report on the percentage of fatalities actually caused by fire and its effects, the National Transportation Safety Board has reported that all the fatalities in several accidents occurred as a direct result of fire and its effects. Dependent upon how many of the 1,015 fatalities were caused by fire and its effects, it is possible to speculate that up to 35 percent of the fatalities in the total number of post-crash fire accidents might have been prevented had the fire hazard been minimized. (A compilation of post-crash fires involving U.S. air carrier aircraft is presented in Appendix A).

Almost 30 percent of all fatal general (private) aviation accidents occurring between 1962 and 1969 involved fire and 60 percent of those involving fire were fatal. In helicopter accidents between 1964 and 1969, 30 percent of the major accidents involved fire and 45 percent of these accidents involving fire were fatal compared to 28 percent of the non-fire accidents.

A study of a crash-fire scenario reveals that the structural load pattern, the break-up of the structure, the initiators and progress of a fire, the fuel sources, and the techniques for evacuating passengers and controlling a crash fire all play a part in reducing fatalities. The cabin fire hazard is much greater when the fuselage ruptures than when it remains intact. Fire prevention concepts focus on special fuels, fire-resistant materials, and fuel tank or fuselage inerting systems (engine and fuel fires are not discussed in depth in this report as they are a separate issue specifically excluded).

4.3 Pre-Fire Initiation Considerations

4.3.1 Determination of Fire Potential

Ignition of polymeric materials is an extremely complex process. It depends on the nature and characteristics of the ignition source, the availability of adequate oxygen, and the physical and chemical properties of the polymer. Important properties of the polymer influencing its "ignitibility" include thermal diffusivity, thermal conductivity, density thickness, specific heat, and activation energy. Once ignited, polymers burn intensely, releasing large amounts of energy (typical heats of combustion for various materials are presented in Appendix B). This energy is transferred by radiation and convection to other combustible materials causing ignition and, hence, propagation of the fire.

Some polymeric materials maintain their structural integrity as they burn while others melt and sag. The latter materials may represent a greater hazard when they are used in load-bearing applications rather than in decorative ones. Other characteristics (e.g., melting and dripping, smoke evolution, rate of heat release, and

burning rates) are additional concerns that can be evaluated only in a finished product. The best evaluation for these materials is in their "use" configuration (see Section 4.4).

Time is a critical element in a fire and an increased effort should be made to learn how to acquire more time for a given ignition intensity. Extinguishment characteristics also need to be defined in sufficient depth.

Flashover is one insufficiently explored aspect of fire dynamics. One type of flashover involves ignition of an accumulation of flammable vapors from pyrolyzing organic materials. Concentrations of CO, H_2, and organic vapors tend to increase ithe upper part of the cabin during a localized fire, and whenever a mixture of these gases with oxygen exceeds the lower flammability limit, an explosion ignition – flashover – may occur. Ignition might involve contact with the original flame or firebrands therefrom or occur spontaneously as a result of heat build up.

The geometry of an area has a very important effect on flashover, particularly in regard to retaining the heated gases and focusing the explosively ignited gases. The ventilation system also may have an important effect.

The fire potential of individual materials has been to some extent determined in small-scale static tests; however, the fire potential of combinations of materials in use in a real environment has not been adequately explored and no accepted predictive methodology (computer modeling, scale modeling, characteristics modeling, etc.) exists. In view of the relatively similar geometry of commercial transport aircraft and increasing capabilities in modeling techniques, a very serious effort to apply modeling techniques to this fire situation should be undertaken.

4.3.1.1 Cabin Ignition Sources

Although a consideration of ignition sources *per se* is not within the scope of this report, the proper evaluation of materials requires that they and the probability of fire development be understood.

4.3.1.1.1 Cigarettes, Matches, Lighters

Temperatures achieved by small heat sources (e.g., cigarettes, matches, lighters) are sufficient to ignite several materials including some synthetic polymers, both solid and liquid. Whether or not such sources will ignite these items depends on the material configuration and the atmospheric dynamics. The following are some typical temperature measurements of small ignition sources:

Item	Condition	Temperature
Cigarettes, center	No draft	1,050°F (565°C)
Cigarettes, center	Draft	1,350°F (732°C)
Cigarettes, center	Insulated	1,150°F (621°C)
Cigarettes, surface	No draft	550°F (228°C)
Cigarettes, surface	Draft	800°F (427°C)

Item	Condition	Temperature
Paper Match	No draft	1,508°F (820°C)
Wood Match	No draft	1,346°F (730°C)
Cigarette Lighters	No draft	1,200–1,500°F (649–816°C)

Results from testing a typical cross section of upholstery materials using a cigarette and other small ignition sources revealed that cotton-rayon materials were ignited by these sources, while certain 100 percent synthetic fibers were not*. Synthetic materials become involved in combustion where blends of cotton-rayon are combined with the synthetic fibers or where cotton is used for cushioning materials since the easily ignited material serves to ignite the more difficult materials. Using cigarettes as a source of ignition for cotton-rayon-cellulose-latex foam materials or blends, the probability is higher for cigarette ignition than with materials that are made of selected synthetic materials. It also should be pointed out that cigarette ignition generally involves a smoldering phase so that considerable time may elapse between ignition, flame growth, and flame spread.

Many design techniques have been developed to reduce cigarette ignition. These include incorporating a heat sink material beneath the surface of a fabric (e.g., an aluminized scrim material beneath a cotton-polyester material will inhibit cigarette ignition), back coating of fabrics with styrene butadiene rubber (SBR) and acrylic solutions, and using tight weave designs with high-density fabrics. Specific treatments have been developed to assist materials in passing the horizontal flame test, but none have been developed for back-coating or surface-treating polypropylene materials to pass the vertical FAA test. Other techniques, such as using fiber glass or high-temperature polymers, are being developed so that materials will pass a small ignition test and possibly a larger ignition test.

4.3.1.1.2 Equipment

Rotating equipment may constitute a fire or explosion hazard. Causes include excessive case temperature due to rubbing friction, dust or clips from rubbing contact, or the throwing of hot parts with mechanical failure.

Electrical and electronics equipment may be an ignition source in normal operation and should be explosion-proofed or enclosed in a vapor-safe compartment. Thermal protection should be used where necessary to ensure that surface temperature cannot exceed 450°F (232°C). Design of the equipment should be such that a remote or catastrophic failure must occur to create an ignition source. Parts that are electrically insulated from the basic airframe can constitute a hazard unless connected to it through lightning arrestors or shielding.

*Unpublished studies of J. Loftus, National Bureau of Standards and NFPA data (Cigarette Fire Mechanism, 1956).

Wiring also may initiate ignition due to heavy overload, fraying of insulation, or breaking of the wire. Insulation of the wire should be selected with regard to fire retardance and the products of combustion of the insulation. In addition, wiring should not be installed in a manner that permits contact with flammable fluid lines. In areas where wiring must be located in close proximity to fuel lines, the wiring support should be located well above the lines to prevent the loose end of a broken wire from contacting flammable fluid pipes. (It has been shown by test that in such cases the arc may burn through the line and set fire to its contents before circuit protection has time to act.)

Terminals must be covered to prevent accidental shorting or grounding, and all plugs and receptacles should be sealed when locked in the connecting position. It is desirable that the seal be established before electrical contact is made and be maintained until after contact is broken.

Circuit protection must be provided for all circuits exposed to transient current input in excess of normal wire rating. This circuit protection may either be installed outside abnormal vapor zones or be explosion-proofed.

Main power cables (including generator cables) should be: (1) isolated from flammable fluid lines in the fuselage, (2) shrouded by electrically insulated flexible conduit, or its equivalent, in addition to the normal cable insulation, and (3) designed to allow a reasonable degree of deformation and stretching without failure.

4.3.1.1.3 Food and Beverage Preparation and Service

Airline operators generally supply food and beverage to passengers when the flight schedule spans an accustomed meal period. Such service has taken many forms from sandwiches and box lunches to elaborate gourmet meals cooked on board. Although specific equipment and facilities vary widely, large amounts of polymers, constituting a substantial fire load, are involved in food preparation, containment, and serving. Large amounts of flammable trash and other leftovers remain to be taken care of after service is completed.

Service of alcoholic and non-alcoholic beverages is provided to passengers by airline personnel under controlled circumstances with very limited fire potential. Although alcoholic beverages were, on at least one occasion, used by arsonists to spread a cabin fire, they are normally well contained in glass containers (before being served) or are diluted sufficiently (when in drinking utensils — normally plastic containers) to be relatively safe. Disposal of plastic drinking utensils is, however, a potential problem.

Prepared meals are delivered to aircraft in metal containers that normally fit into galley receptacles. Each complete meal unit contains pre-cooked food; trays and dishes (usually polymeric); plastic or metal knives, forks, and spoons encased in plastic bags; and occasionally a paper mat or container to surround some portion of the meal (e.g., the meat or bread roll). The pre-cooked meal is inserted into a warming/holding oven in the galley unit. Warming temperatures normally are not

sufficiently high to cause fires in the food unit; however, the electrical resistance heating units are sufficiently hot to ignite polymers accidently contacting them.

Food preparation, loading, and serving arrangements emphasize speed of service, durability, aesthetics, and passenger satisfaction, and little consideration has been given by the catering services to fire safety aspects. Some minor improvements appear possible without substantial cost (i.e., discontinuing use of paper containers and plastic knives, forks, spoons; employing temperature-resistant plates, cups, saucers, etc.).

A substantial new hazard has been created, particularly in the wide-bodied jets, by the provision of galleys for the full preparation and cooking of meals. Grease fires, particularly from cooking steaks, etc., do occur despite design efforts to prevent or counter them. Considering the dispersion and long-term concentration of grease particulates into the galley exhaust system and service area, as well as the low temperature at which such fires can be initiated, it appears that the issue of cooking rather than "holding" on board passenger aircraft should be reanalyzed to assess the risk. A substantial number of meals are involved, working conditions are difficult (particularly in the lower-level galleys), and the egress/service elevator arrangement is such that the potential for occurrence of undesirable events is high.

After cooking/heating, food units are delivered individually by airline personnel under reasonably good conditions. Consumption by passengers takes place usually under normal circumstances.

In general, the process of preparing and supplying food to passengers has less adverse fire potential than disposal of the meal residues. Passengers in smoking sections of aircraft usually light cigarettes, cigars, etc., during or after consumption of the meal-concluding beverage. The food tray at this time usually contains a used napkin, paper doily, plastic utensil bag, plastic dishes, and other leftovers; ashes and occasionally cigarette butts are discarded into such debris. When collected and dumped into the trash container or bag at the galley, unnoticed live ashes can be present, contributing a significant hazard.

The problem relating to fire safety of trash collection and disposal require additional study. Possible improvements that might increase trash density (e.g., use of compactor), decrease oxygen content of surrounding air (e.g., nitrogen inerting) or reduce polymer content of trash (e.g., china dishes and metal knives, forks, and spoons) should be considered. The scenario approach discussed in Chapter 3 could be quite useful in this regard.

Airline operators supply and install galley assemblies in accordance with FAA reglations, health codes, and their own food policies and practices. Decoration generally conforms to other portions of the aircraft cabin and limited amounts of decorative polymer facings, some of which are not functionally necessary, are used on galley equipment. In some cases electrical heating elements (for coffee making, etc.) are not protected and trash and debris from food service can fall on the exposed high-temperature surfaces. Galley trash bins usually are not protected by detectors in inerting systems.

Considering that approximately 55 percent of reported aircraft fires are galley initiated and that increased passenger loads magnify trash disposal and other problems, it appears that a substantial effort to fire harden galleys should be undertaken. This effort should include development of design guidelines and check-off lists so that improved fire safety of galleys will be achieved.

4.3.1.2 Fireload

One of the classic approaches to understanding the potential severity of fires in a given space has been to measure the "fire load" or potential heat release under fire conditions. The fire load on aircraft can be divided into three categories:

1. Part 25 Materials installed by the air frame manufacturer.
2. Part 25 Materials installed or Part 121 Materials put on board by the airlines.
3. Materials worn or carried on board by passengers.

A typical breakdown of the relative amounts of nonmetallic materials on a fully boarded 270-passenger aircraft is shown in Figure 4 (a list of the potential heats of combustion of a number of materials is shown in Appendix B) and can be converted to potential heat by multiplying by 8,000 Btu/lb.* The 8,000 Btu/lb

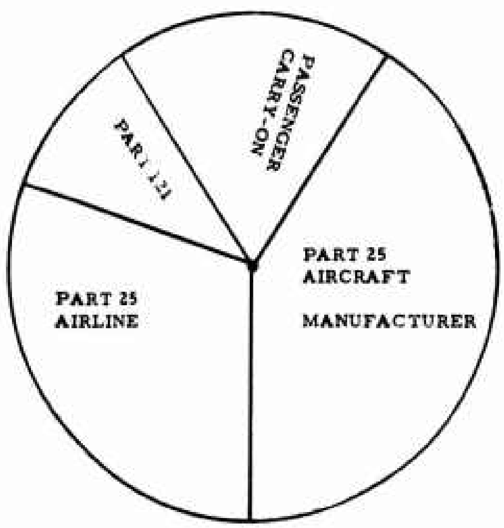


TABLE 4

	WEIGHT	% TOTAL
Part 25 Aircraft Mfg.	8361	43.7
Part 25 Airline	5960	31.2
Part 121 Serv. & Cabin Equipment	1559	8.2
Passenger Carry-on	3240	16.9
	19120	100.0

Note: See Table D-2, Appendix D, for a detailed breakdown of the noted materials.

Figure 4. Nonmetallic materials on fully loaded 270 passenger widebody aircraft (exclusive of cargo, fuel, oil and lubricants)

value represents an estimate of the heat that would be released by all of the nonmetallic materials in Figure 4 under full fire conditions (i.e., under conditions where they are completely consumed). Under these assumptions there would be

*The 8,000 Btu/lb value is approximately that of wood and paper combustible materials; multiply by 0.555 to obtain cal/gm.

1.53×10^8 Btu** of potential heat available in the 270-passenger-wide-body aircraft. The length of the aircraft cabin between the flight deck bulkhead and the aft bulkhead is 134 feet and the width is approximately 19 feet; thus, the floor area is approximately 2,500 square feet and the fuel load is 7.5 pounds per square foot or 60,000 Btu per square foot, approximately the same as that in an office or a theater. Without considering the arrangement of these fuels (i.e., walls, ceilings, seats, rugs, etc.), it would be difficult to discuss the early fire growth implications of the relatively high fire load.

4.3.1.3 Personal Danger

The crew may be involved in two types of fire. First is the incidental fire that is represented by the galley fire, the infrequent instrument panel fire, or the fire that could occur when pouring an alcoholic drink ithe presence of an ignition source (e.g., cigarette). Second is the catastrophic fire involving engine fuel or a major interior fire.

Elimination of all non-treated cellulosic types of fiber in crew clothing would reduce the probability of ignition but would not ensure a protective garment although the use of Kynol,® Nomex,® aluminized fiber glass, or treated cotton or wool materials would confer a certain degree of fire protection. Naturally, additional design parameters (e.g., the use of slacks, hooded capes, thermal gloves, and a self-contained breathing apparatus) would add to safety.*

Crew safety in a major fire could involve the provision of special protective clothing at exits presumably to be donned at the time of a potential fire. However, since the majority of crash fires occur unexpectedly, this provision would improve only the situation in the fewer forewarned accidents.

4.3.2 Current Fire Prevention Control Systems

4.3.2.1 Prevention

Fire prevention starts with aircraft design and follows through all operational actions. Ignition sources are eliminated or controlled to the extent funcitonally possible and are separated from possible fuels. Fire detection systems that provide for quick operation of fire suppression systems before a fire builds up are installed in engine nacelles and in unoccupied areas of the aircraft. A systematic approach to fire prevention initially adopted for the NFPA Committee on System Concepts is illustrated in Figure 5.

There are no fire detection systems or effective controls on the materials or ignition sources carried on board by passengers. The crew and passengers are ex-

**Multiply by 1,055 to obtain joules.

*There is some concern that the increased use of hair sprays may significantly increase the flammability of hair; hydrocarbon aerosol propellants also may serve as a potential flammable liquid.

pected to detect a cabin fire, and the crew is expected to put it out, using hand extinguishers, before it is too large to control.

Fire detectors and suppressors systems generally are not installed in lavatories, but airlines now request passengers (verbally and in writing) not to smoke in those areas. The mere request, however, is not sufficient.

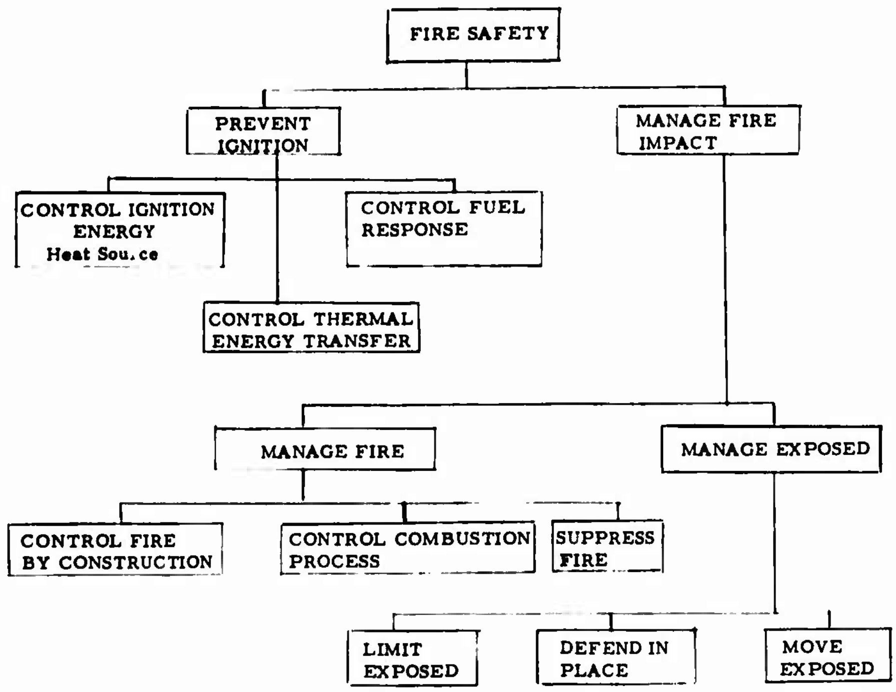


Figure 5. Systems fire safety network.

Aircraft also are of a size where fire barriers on compartmentalization are used to separate cargo, crew, and passenger compartments. Such separations help to contain fires; however, consideration by designers of the fire barrier concept beyond this has been minimal. Servicing of fuel, hydraulic, and oxygen systems presents such severe fire hazards that special conditions, facilities, and procedures are required to prevent fire. In addition, aircraft are now designed in a manner to prevent fire following a lightning strike.

In essence, fire prevention, control, and extinguishment must be treated as an aviation system problem since all parts of the fire problem are related (e.g., tradeoffs in safety and economics must be made in using materials that are difficult to ignite but that when ignited, produce bad fire, smoke or toxic gas conditions). Details on various aspects of this problem are presented in Appendix C, Fire and Smoke Detection and control Systems, and Appendix D, Post-Fire Initiation Considerations.

4.4 Design Considerations

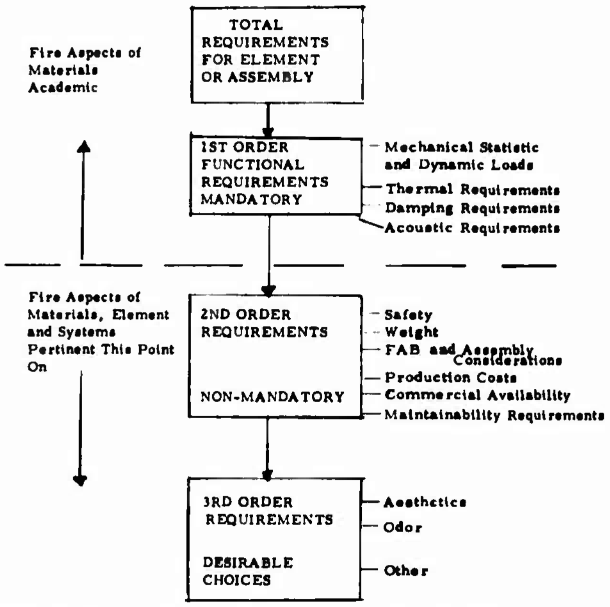
4.4.1 Introduction

The purpose of this section is to provide a guide for the design of polymeric material components insofar as the material selection is relevant to fire safety. Considerations for material selection are discussed as they pertain to some hardware parameters controlled by the designer. These parameters include considerations of part function, geometry, location, and the influence of significant material and temperatures.

4.2.2 Component Considerations for Material Selection

4.4.2.1 Part Function

All hardware items have a primary purpose or function. The means to satisfy this function is through a requirement specification or design criteria. Once the design criteria have been established, the designer begins the design process. This usually involves a series of trade-off studies, many times resulting in compromises among requirements. If part function cannot be provided or the required criteria met consideration of other desirable features becomes academic. This premise establishes the sequence of design flow for any hardware element regardless of second or third order requirements of desirable features that merely provide an additional basis for trade-off study selection of materials for a given application. Flow sequence for candidate component design relative to function and fire characteristics is illustrated in Figure 6.



*Interior non-structural bulkheads
Seats
Carpeting
Galley Hardward
Ceiling Paneling
Window Moldings
Baggage Containers (Overhead)
Lavatory Hardware

*Figure 6. Flow Diagram for Candidate Componentry**

4.4.2.2 Geometry

The geometry of cabin hardware (interior non-structural bulkheads, seats, carpeting, galley hardware, section paneling, window molding, luggage containers, lavatory fixtures) is very important in terms of fire flashover and particularly that involving retention of heated gases and the focusing of explosively ignited gases. Flame propagation rates vary according to the path of the flame front (i.e., vertically, horizontally, or at some intermediate angle). These geometry considerations are virtually impossible to control meaningfully but should be given attention if design function can be accommodated (see Chapter 3).

4.4.2.3 Part Location

The location of a part can constitute a parameter for material selection by virtue of the response of the available polymers to the elements of a given fire scenario — i.e., a material's propensity to drip, emit smoke and toxic fumes, self-extinguish, respond to heat flux, other significant parameters of a polymer as they relate to its combustion performance can be extremely important from the standpoint of fire propagation or retardation in a given scenario. Materials that melt and drip would prove extremely hazardous to cabin components if located in a position that would permit them to ignite other materials.

In addition, location of a part relative to possible elevated temperature, high rate of energy input, environmental (particularly partial pressure of O_2), and heat loss are important parameters for its ignition and sustained burning. Ignition testing of fibrous materials with a bunsen burner has demonstrated that some materials which self-extinguish at room temperature will be completely consumed when the ambient temperature is elevated to 248°F (120°C). Data for a group of materials tested using the FAA FAR 25-Para. 25. 853a method are presented in Table 1.

Bunsen Burner Test

MATERIAL	RT AIR 1		250°F AIR 1	
	FLAME TIME, SEC.	BURN LENGTH, IN	FLAME TIME, SEC.	BURN LENGTH, IN
Nomex® Fabric, Undyed	0	2.5	0	3.3
Wool Fabric, FR Treated	0	2.5	9	10.0 2
Nomex® Carpet, Polyester Back, FR Latex Coating	17	0.6	3.8 min.	8.8 2
Wool Carpet, Polyester Back, FR Latex Coating	8	1.8	48	8.8 2
Wool Carpet	15	3.6	2.4 min.	10.0 2
Dynel Carpet	5	3.3	5	10.0 2

1 Temperature of air in burn chamber

2 Specimen was fully consumed

Table 1 Elevated Temperature vs Room Temperature

It can be seen that material selection parameters for hardware application should include the location within the total design geometry as a function of a given fire scenario. This could mean that the applications in locations where temperatures, prior to or during combustion, are apt to be higher than at other locations within the total fire scenario, one would require the application and usage of a different material system. The designer is thus required to consider another variable in material selection.

4.4.2.4 Detail vs Assembly

Proper evaluation of the combustion quality of a material in a given application requires consideration of the material or combination of materials in an assembly and the material in the adjacent assembly.

Surface texture, color, shape, weave, guage, density, etc., affect the ignition, burn, and smoke characteristics of otherwise chemically identical materials when tested by the same methods, therefore, detail parts cannot be averaged to obtain their combined characteristics but must be tested as the complete end hardware assembly. An example of this phenomenon is presented in Table 2. With this combination of materials, in vertical burn tests conducted per FAA FAR 25.853a,

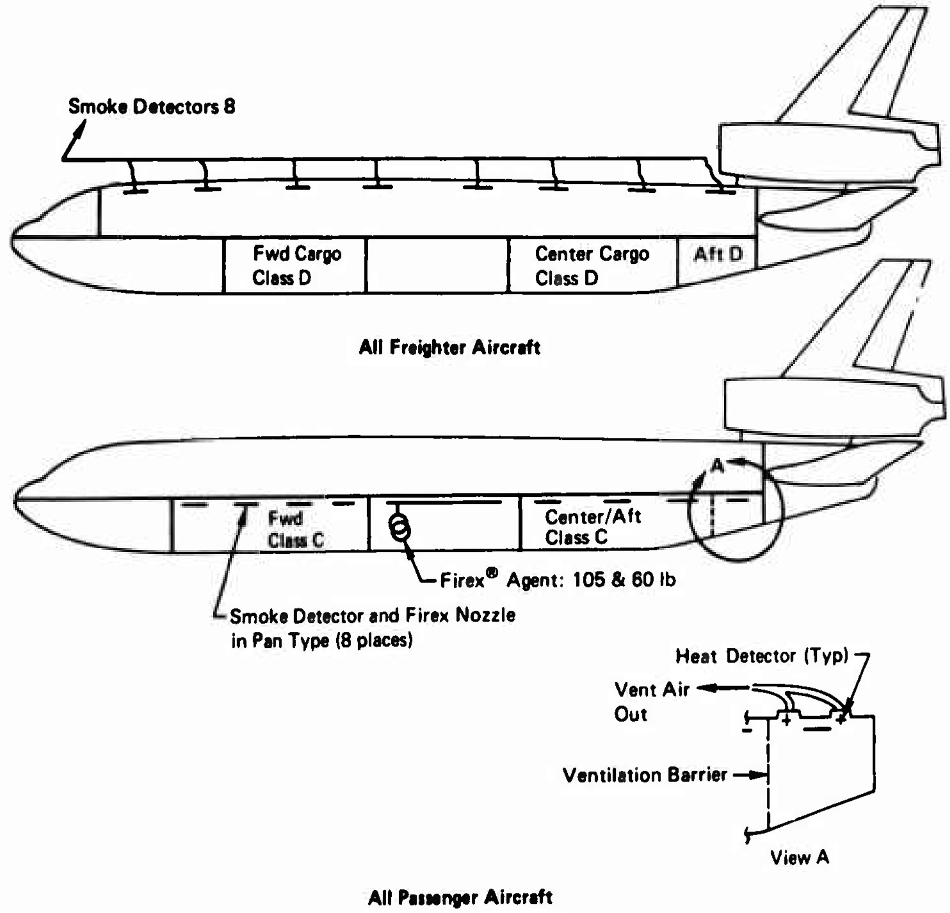
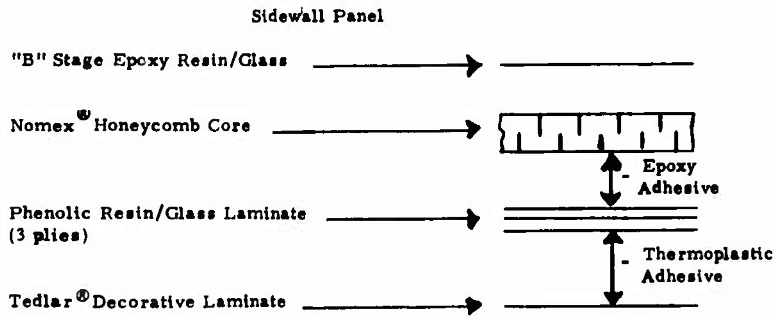


Figure 7. Current detector systems.

FAA 60 Sec. Vertical Burn Tests
(per FAR 25.853a, Amend 25-32)



RESULTS OF COMPLETE PANEL ASSEMBLY		
Flame Time (Secs)	Burn Length (inches)	Flame Time of Drippings (Secs)
0	4.70	ND
0	4.90	ND
2	4.50	ND
AVG. 1	4.70	ND
RESULTS OF PHENOLIC RESIN/GLASS LAMINATE		
0	3.60	ND
0	3.60	ND
0	3.60	ND
AVG. 0	3.60	ND

Table 2

Amendment 25–32, the burn length of the complete panel assembly averaged 1.1 inch longer than that resulting in an identical test conducted on a phenolic resin/glass laminate.

4.5 Conclusions and Recommendations*

Conclusion: The fire safety aspects of aircraft subsystem design have not been sufficiently recognized, emphasized, or valued in trade-offs to permit optimum selections of polymeric materials in those systems. *Recommendation:* Fire scenarios should be developed and become the bases for risk analysis and trade-off studies in the selection of system requirements. Fire safety should be included as a prime element.

Conclusion: Certain high risk areas in aircraft merit additional fire hardening and detection effort. These comprise *inter alia* the galley, lavatories, and flight station. *Recommendation:* Design and development efforts to harden specific areas, including selection of materials with better fire retardant qualities and decreased toxicity of combustion products, should be increased.

Conclusion: A fire can be transmitted with extreme rapidity from one end of the aircraft to the other (flashover phenomenon). This condition can manifest itself within 2 to 3 minutes after a fire initiation. The plastic air duct system is a principal offender in this regard. *Recommendation:* Materials used in and the design of the upper part of a cabin (compartmentation) should be selected to minimize the spread of a fire and the air duct system outside the passenger occupied area should be of metallic construction.

Conclusion: Prevention and control of fires in cabin areas of aircraft depend on the use of fire-retardant materials plus quick action by crew or passengers to extinguish a small fire before it develops beyond control. *Recommendation:* All areas (such as lavatories) of the aircraft intermittently occupied by personnel, either crew or passengers, should contain fire and smoke detection equipment.

Conclusion: Flight crews normally are closer to a fire than other passengers aboard the aircraft and are depended on by the passengers for direction and capability in the event of such an emergency. Flight crews and cabin attendants are trained in firefighting, and portable fire extinguishing equipment for their use is provided at strategic stations throughout the cabin; fire-resistant clothing or covers are not provided. *Recommendation:* Airline flight crews (both cockpit and cabin) should be furnished, for everyday wear, clothing fabricated from commercially available fire-resistant fibers (such as treated wool, treated cotton, treated polyesters, aramids, and phenolics) to provide increased protection against fire.

Conclusion: Polymeric and other organic materials such as plastic utensils,

*It will be apparent to the reader that there is some duplication between this chapter and others in this volume. This arises from the various points of view from which the subject has been examined. It should also be noted that related material is presented and committee conclusions drawn in Appendices C and D.

paper, and other items utilized by the cabin attendants during meals and other services represent a large fire load. Storage practice of these materials has, on occasion, been observed to consist of wrapping waste plastic material in plastic bags for storage in an empty lavatory. *Recommendation:* Small lightweight in-flight rubbish compactors should be provided for the compacting and storage of flammable materials during flight; bagging material should be highly resistant to ignition.

Conclusion: With the exception of electrical and fuel ignition sources on the vehicle, the primary cause of in-flight fires is the galley, the second is the cigarette. The heat from a cigarette in most cases is insufficient by itself to ignite the materials used in aircraft cabin interiors; however, in the presence of a transition material (e.g., fingernail polish, newspapers, and paper towels) cigarettes can and have initiated fires in all areas of in-flight aircraft. *Recommendation:* Smoking should be eliminated in all aircraft cabins and lavatories and the practice of in-flight cooking should be reviewed from the viewpoint of risk-benefit with consideration given to its possible elimination.

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CHAPTER 5

AIRCRAFT MATERIALS

5.1 Introduction

As noted earlier in this report, commercial and military aircraft fire safety must be concerned with total system design including ignition sources, fire detection, and fire control. Materials used in aircraft are a part of each of these elements.

Because of the special considerations involved with aircraft, particularly in flight, polymeric materials should have the highest level of fire safety performance consistent with pragmatic limitations of availability, cost, and other performance properties (e.g. mechanical durability, weight, aesthetic appeal, mar resistance, ease of cleaning and fabrication).

Areas of fire safety importance that have been designated by the National Transportation Safety Board are:

1. Lavatories, galleys, and cargo bays that are not under continuous surveillance.
2. Areas occupied by passengers and crew.
3. Areas such as the fuselage where polymeric materials (e.g. linings, wire insulation) are secondary components.

The first two areas constitute the interior of an aircraft and polymeric materials are present in several applications including:

1. thermal and acoustical insulation, walls and ceilings, safety chutes, survival gear, oxygen systems, and other aircraft systems (provided by aircraft manufacturers).

2. seats, carpeting, draperies, pillows, blankets, and other passenger support items (provided by the airlines and operators when not supplied by the manufacturers).

3. passenger carry-on materials (provided by the traveling public).

In many instances, military transport aircraft utilize the same type and form of materials as commercial aircraft, the principal difference being the elimination of the materials required by the airlines for interior decoration. Military combat aircraft (fighters, bombers, etc.) are much more limited in the use of polymeric materials, retaining only those essential to operation of the system.

Current test methods specified by the FAA and military agencies are based on technical developments of the scientific and industrial communities. They have been used successfully to develop substantially safer aircraft by permitting the replacement of highly flammable materials with improved materials. However, these test methods usually measure a limited number of individual characteristics and do not provide an integrated assessment of all fire safety parameters. The standards were developed from tests reflecting the then state of the art and usually do not take

into account aging phenomena or design considerations. Furthermore, correlation of test results with actual fire situations is uncertain or unknown. There have been several cabin-initiated fires in commercial aircraft that were constructed in full compliance with the present regulations.

Many polymeric materials are used in blends with other polymers or as composite structures (e.g., in large structures such as wall panels). The fire safety performance of these structures is complex and difficult to predict since the evaluation of individual components does not provide complete information about the performance of the composite or multicomponent system upon fire exposure.

Materials carried on board by and/or for passengers cover a wide range of liquids, solids, aerosols, and other compositions of varying degrees of potential fire hazard. Taken separately or as a group, these materials are substantially more flammable than the materials provided by the aircraft operators of manufacturers and constitute a significant factor in the overall fire safety of the aircraft — one that is not very susceptible to improvement except by containment and, to some degree, by regulation. More importantly, these materials may serve to kindle less flammable materials.

To date, the concern for the fire safety aspect of material selection has focused on resistance to ignition or prompt self-extinguishment; however, the potential smoke generation and toxic gas evolution characteristics of the selected material now are receiving attention. Evidence is accumulating that relates present self-extinguishing formulations in polymeric materials with increased smoke and toxic gas release in a conflagration.

5.2 Evaluation Criteria and Methodology

Evaluation and selection of polymeric materials is a complex and difficult task. It is not currently possible to define fire safety with precision without reference to specific parameters or conditions of testing. The fire safety aspects of a polymer depend on many factors including actual condition of use and, particularly, the geometry and orientation of usage, proximity of other materials, environmental conditions, source and site of ignition, as well as the intrinsic properties of the polymer such as composition, thermal stability, and heat transfer characteristics. In addition, the effects of decomposition products (smoke and toxic gases) must be considered. As indicated above and demonstrated more fully in Chapter 6, the methods being used to evaluate polymer fire safety are only partial measures under limited conditions of testing. Results can be interpreted only with reference to the test procedures employed and with full awareness of the prevailing limitations in test methodology.

A further distinction must be made with regard to the intent of various flammability test methods. In the hierarchy of procedures used for materials selection, distinction should be made among tests (see page 128 for classification of test methods) and the results should be meaningfully and carefully qualified.

Investigation of evaluation methods has led to identification of performance criteria that are related to fire safety. These criteria – used in the evaluation of existing materials in specific applications, in the development of new materials, and in the design of improved material combinations are:

1. Ease of ignition
2. Rate of flame spread
3. Heat release (rate and/or total)
4. Smoke
5. Toxicity of combustion products
6. Ease of extinguishment

The criteria are imprecise and depend on imperfect test procedures since the relationship of results obtained in the laboratory to equal fire situations is generally not known. For example, ease of ignition clearly depends on the heat intensity from the ignition source. The ranking of polymeric materials with respect to ease of ignition may be different for low heat flux sources than for high heat flux sources. Knowledge of material's composition and experience with its behavior, together with the limited data from laboratory testing conditions, allow, at best, qualitative descriptions of materials with respect to fire safety parameters.

Questionnaires (see Appendix E) designed by the Materials Panel of the Committee were completed by the major commercial aircraft manufacturers, major trunk airline operators, and the U.S. Air Force. The responders identified the polymeric materials used in their aircraft. They told how the materials were used, why they were selected and what improvements might be made. Reduction of the raw data led to recognition of 33 end uses and correlation of materials choice with usage. Review of this data by the Materials Panel led to suggestions for employment of currently available alternate materials as well as developmental materials. These were entered into Table 3 and rated together with the currently used materials.

Comprehensive evaluations of the fire safety aspects of polymeric materials, such as those being attempted by this committee (sey Section 5.3.1) can be categorized as follows:

1. Certain materials appear to need improvement from the fire safety point of view.

2. Other materials appear to be generally acceptable on an interim basis. This acceptance is based on current knowledge, but continued acceptance would require additional information on the six fire safety parameters listed above and would also depend on where the material is used and the quantity in the aircraft.

3. Some improved materials are available that may present less toxicological hazard.

4. New or improved replacement materials are at various stages of development and should be seriously considered as candidates for future use in aircraft. Although these may not be economically attractive at the moment, their cost may be expected to decrease with increased demand.

5. There are presently organic polymeric materials that possess different degrees of combustibility, but none of these are completely noncombustible.

. modifications currently used to decrease the flammability of polymeric materıals may actually increase the smoke and/or toxicity hazard (see Section 5.4). To evaluate smoke and toxicity, better test methodology and tests on well-characterized materials are clearly needed. These can be used to correlate the effects and perform a risk analysis.

APPROXIMATE USAGE OF POLYMERIC MATERIALS IN TRANSPORT AIRCRAFT

Application	Polymeric Material Per Aircraft (lb)
Acoustical insulation	250-800
Blankets	40-500
Cargo liners	120-
Carpeting	200-800
Ceiling	-1200
Curtains	5-140
Ducting	~1000 ±
Elastomers	~500 ±
Emergency slides	48-1100
Floor	150-1000
Floor coverings (galley and lavatory)	18-250
Life rafts	350-1175
Life vests	100-575
Lavatory paper (tissue and towels)	15-70
Movie film	150-250
Paint	~12 ±
Passenger service units	600-800
Partitions and sidewalls	200- ~2000
Pillows	7.5-150
Thermoplastic parts	~500 ±
Seat belts	14-358
Seat cushions	388-2000
Seat upholstry	175-950
Seat trim	95-429
Wall covering	~100 ±
Windows	400- >800
Window shade	~200 ±
Wire insulation	300- >500

Table 3

In summary, the methodology available and the evaluation criteria selected for assessing the fire safety of specific materials used in aircraft are only qualitative and tentative; they are presented, with full awareness of their limitations, as a stepping stone for further progress. A continuing reevaluation of these materials in the light of newly available methodology and knowledge is mandatory.

5.3 Fire Safety Evaluation

5.3.1 Background

The types and quantity of the polymeric materials that constitute the fire

load in commercial aircraft as provided by the response to the questionnaire are listed in Table 3. The performance – ease of ignition, rate of flame spread, heat release, smoke, toxicity of combustion products, and ease of extinguishment – used for the qualitative assessment of fire safety in commercial and military aircraft are summarized for 32 applications in Table 4. It clearly would be desirable to define the behavior of each material with respect to each parameter in quantitative terms or, at least, to refer to conditions of testing that have been identified as optional; however, the facts reported for such quantitative definition are not available from the technical literature. Therefore, ratings of "good," "satisfactory," "unsatisfactory," and "further study needed" are an attempt to provide an overall assessment of fire safety based on the knowledge, experience, and opinions of the members of the committee. In reaching its assessments, the committee considered the results of many tests, test methods, and standards in use today as well as the basic chemical compositions of the materials used. No attempt was made to define in any detail the chemical nature of the material since this is covered in the committee's report on Materials (Volume 1).

Most of the materials are not completely satisfactory for the specific application based on a total evaluation of functionality, "in-place" cost, weight penalty, aesthetics, durability, maintenance and fire safety. Trade-offs and compromises obviously were made is selecting the materials used for each application. Recognizing the difficulties that exist in the selection of materials, the suggestions found in Table 4 with respect to possible future development are made on the basis that these will necessarily require extensive testing and evaluation before a decision is made to use them. However, the importance of Table 4 as a summary of current knowledge should be apparent to the reader.

In terms of ease of ignition and rate of flame spread, the materials employed have been significantly improved over the years. Nevertheless, concern over smoke and toxic product formation has received major attention only in the recent past, and materials in use today do not necessarily reflect the new dimension. Integration of new knowledge acquired is a continuing process.

5.3.2 Approach to Fire Retardation of Polymers

All organic polymers will burn under specific conditions, but it is possible to modify burning behavior by using fire-retardant compounds such as those containing halogens, phosphorus, antimony, boron, or various combinations of these. Synergism among these materials provides increased fire-retardant efficiency. The requirements on the fire retardant are a function of the polymer itself, the structure of the retardant, and the design of the flammability test.

At least six speculative mechanisms have been proposed for fire retardation:

1. Generation of noncombustible gases that dilute the flame oxygen supply as well as exclude oxygen from the polymer surface.

2. Degradation of the retardant into radicals or molecules that react endothermically with flame species or substrate species.

TABLE 4 Materials Flammability Appraisal

	Presently Used and Available																			
Use	Generally Acceptable	1. Ease of Ignition	2. Flame Spread	3. Heat Release	4. Smoke	5. Toxicity	6. Ease of Extinguish	Needs Improvement	1. Ease of Ignition	2. Flame Spread	3. Heat Release	4. Smoke	5. Toxicity	6. Ease of Extinguish	Possible Future Development	1. Ease of Ignition	2. Flame Spread	3. Heat Release	4. Smoke	5. Toxicity	6. Ease of Extinguish
1. Acoustical thermal insulation	a. Fiberglass insulation with paper backing	+	+	+	*	+	+	Flexible polyurethane foam	-	-	-	-	-	-	a. Crosslinked phenolic foam	+	+	+	*	+	+
	b. Glass wool	0	+	+	*	+	+								b. Ames polyurethane foam	+	+	+	*	*	+
															c. Polybenzimidazole	+	+	+	*	*	+
															d. Polyimide	+	+	+	*	*	+
															e. Fiberfrax®	+	+	+	*	*	+
2. Adhesives	a. Polyimides	0	0	0	+	0	0	a. Epoxides	0	0	0	-	*	0	a. Polybenzimidazole	+	+	+	*	*	+
								b. Neoprenes	0	0	0	-	-	0	b. Polyphenylquinoxaline	+	+	+	*	*	+
								c. Buna N phenolics	0	0	0	*	*	0							
								d. Acrylics	-	-	-	*	*	*							
3. Air duct								Urethane foam	-	-	-	-	-	-	a. Polyimide foam	+	+	+	*	*	+
															b. Polybenzimidazole	+	+	+	*	*	+
4. Baggage	a. Phenolic/glass laminate	0	0	0	0	*	0	a. PVC-coated veneer honeycomb	*	*	*	*	-	*	a. Furan/glass laminate FR paint	+	+	+	+	+	+
								b. PVF on phenolic/glass honeycomb	*	*	*	*	-	*							
5. Blankets	a. Aramid	0	0	0	0	*	*	a. Wool	-	-	0	-	-	0	a. Polybenzimidazole	+	+	+	+	*	+
	b. Aramid/phenolic	0	+	0	0	*	*	b. FR wool/rayon 85/15	0	0	0	-	-	0	b. FR modified aramid	+	+	+	*	*	+
								c. FR wool	0	0	0	-	-	0	c. Polyimide	*	+	+	+	*	*
								d. Wool/PVC	+	+	0	-	-	+							
								e. Wool/modacrylic	-	0	0	-	-	0							
								f. FR cotton	0	0	0	-	*	+							
								g. PVC/PVOH	0	0	0	-	-	0							
								h. FR modacrylic/Kynel®	0	0	0	*	*	0							
								i. FR rayon	0	0	0	-	-	+							

TABLE 4 Materials Flammability Appraisal (*continued*)

	Presently Used and Available															Possible Future Development						
Use	Generally Acceptable	1. Ease of Ignition	2. Flame Spread	3. Heat Release	4. Smoke	5. Toxicity	6. Ease of Extinguish	Needs Improvement	1. Ease of Ignition	2. Flame Spread	3. Heat Release	4. Smoke	5. Toxicity	6. Ease of Extinguish			1. Ease of Ignition	2. Flame Spread	3. Heat Release	4. Smoke	5. Toxicity	6. Ease of Extinguish
6. Cabinet								a. FR polyethylene skins, on epoxy/glass, aramid/phenolic core	0	0	0	0	–	•		a. Furan with FR epoxy covering	+	+	+	•	•	+
								b. PVF covering on epoxy/glass, aramid/phenolic core	•	0	0	•	–	•		b. Phenolic with FR epoxy covering	+	+	+	•	•	+
7. Cargo liners	Polyimide resin/glass	+	+	+	•	•	+	a. Rigid polyurethane sheet on aramid honeycomb	0	–	0	–	–	–		a. Bismaleimide resin/glass	+	+	+	•	•	+
								b. Polyester resin laminates	•	•	0	–	•	•		b. Polybenzimidazole/glass cloth	+	+	+	+	•	+
								c. Polyurethane resin laminates	•	•	0	–	•	•								
8. Carpets (FR latex FR backing)	a. Aramid	•	•	•	–	•	•	a. Modacrylic	•	•	–	–	–	0		a. Polybensimidazole	•	•	•	•	•	•
								b. FR wool	•	•	–	–	–	0		b. FR aramid	•	•	•	•	•	•
								c. Wool/nylon	0	–	–	–	–	•		c. Novoloid	•	•	•	•	•	•
								d. Wool	0	–	–	–	–	•								
9. Ceiling panels and covering								a. Vinyl-coated epoxy/glass laminate honeycomb	0	0	0	–	–	+								
								b. PVC-coated cotton	•	•	•	–	–	–								
								c. PVF-epoxy/phenolic over glass-filled aramid honeycomb	•	•	•	•	•	+								
10. Curtains & draperies	a. Aramid	0	0	0	0	•	0	a. Wool	–	–	–	–	–	0		a. Polybenzimidazole	+	+	+	+	•	+
	b. Fiberglass	•	•	+	+	+	•	b. Modacrylic	0	0	0	–	–	0		b. FR aramid	+	+	+	•	•	+
	c. Novoloid	0	0	0	0	•	0	c. FR wool	0	0	0	–	–	0		c. FR aramid/novoloid	+	+	+	•	•	+
	d. Aramid/novoloid	0	0	0	–	•	0	d. FR cotton	0	0	0	–	•	–								
								e. Cotton/rayon	–	–	–	–	•	–								
								f. PVOH/PVC	0	0	0	–	•	0								
								g. Modacrylic/phenolic	0	0	0	–	•	0								

TABLE 4 Materials Flammability Appraisal (*continued*)

	Presently Used and Available																			
Use	Generally Acceptable	1. Ease of Ignition	2. Flame Spread	3. Heat Release	4. Smoke	5. Toxicity	6. Ease of Extinguish	Needs Improvement	1. Ease of Ignition	2. Flame Spread	3. Heat Release	4. Smoke	5. Toxicity	6. Ease of Extinguish	Possible Future Development	1. Ease of Ignition	2. Flame Spread	3. Heat Release	4. Smoke	5. Toxicity	6. Ease of Extinguish
11. Emergency slides								Neoprene-coated nylon fabric	-	-	*	-	-	-	See No. 17 (life vests)						
12. Floor coverings								a. PVC laminates	0	0	0	0	-	0	FR epoxy coating	0	0	0	*	*	+
								b. Vinyl/ABS	0	-	-	-	-	-							
13. Floors	a. Metal-faced balsa	+	+	0	*	+	*	a. Epoxy/fiberglass aramid honeycomb	0	+	0	-	*	0	a. Polyimide/fiberglass-faced aramid honeycomb	+	+	0	*	*	+
	b. Metal-faced aramid honeycomb	+	+	0	*	*	*	b. Phenolic-faced Styrofoam®	0	*	*	-	*	*	b. Phenolic/fiberglass-faced aramid honeycomb	+	+	0	*	*	+
															c. Furan/fiberglass-faced honeycomb	+	+	0	*	*	+
14. Hoses	Silicone	0	0	*	0	0	*	a. Neoprene	0	0	*	-	-	-	a. Phosphazenes	+	+	+	*	*	+
								b. Buna N	0	0	*	-	-	*							
								c. Viton®	0	0	*	0	-	0							
15. Lavatory paper								Paper and tissues	-	-	-	0	0	-	FR paper: improved dispensing and discard	+	+	+	+	*	+
16. Life rafts								a. Urethane-coated nylon fabric	-	-	-	-	-	-	See No. 17 (life vests)						
								b. Neoprene-coated nylon fabric	-	-	*	-	-	-							
17. Life vests								a. Neoprene-coated nylon fabric	-	-	*	-	-	-	a. FR neoprene-coated nylon fabric	+	+	+	-	-	+
								b. Urethane-coated nylon fabric	-	-	-	-	-	-	b. FR neoprene-coated aramid fabric	+	+	+	-	-	+
															c. Fluoroelastomer on aramid	+	+	+	*	-	+
															d. Phosphazene-coated aramid	+	+	+	*	*	+
18. Movie film								a. Polyester	-	-	-	-	*	-							

TABLE 4 Materials Flammability Appraisal (*continued*)

	Presently Used and Available															Possible					
Use	Generally Acceptable	1. Ease of Ignition	2. Flame Spread	3. Heat Release	4. Smoke	5. Toxicity	6. Ease of Extinguish	Needs Improvement	1. Ease of Ignition	2. Flame Spread	3. Heat Release	4. Smoke	5. Toxicity	6. Ease of Extinguish	Future Development	1. Ease of Ignition	2. Flame Spread	3. Heat Release	4. Smoke	5. Toxicity	6. Ease of Extinguish
19. Paints (must be considered with substrate)								a. Nitrocellulose, tung oil lacquers	-	-	-	-	-	-							
								b. Alkyds and urethane	-	*	0	-	*	*							
								c. Epoxy and polyester primes	-	*	0	-	*	*							
								d. Fire retardant paints	0	0	0	-	*	0							
								e. Intumescent paints	0	0	0	-	*	0							
20. Partitions, clothes closet, and side walls								a. PVC or PVF on phenolic/ fiberglass honeycomb	*	0	0	*	-	*	a. FR epoxy costing, furan/ glass face, phenolic honeycomb	0	0	0	*	*	*
								b. PVC laminate over veneer faced honeycomb	*	*	*	-	-	*	b. FR epoxy coating phenolic/glass face phenolic/glass honeycomb	0	0	0	*	*	*
								c. PVC laminate over epoxy/ glass faced honeycomb	*	*	*	-	-	*	c. Same as "a" with aramid honeycomb	0	0	0	*	*	*
								d. FR epoxy, aramid/phenolic core, PVF film	0	0	*	*	*	*	d. Same as "b" with aramid honeycomb	0	0	0	*	*	*
21. Pillows	Cover//fill							Cover//fill							Cover//fill						
	a. Aramid//aramid	0	0	0	-	*	0	a. Cotton//PET	-	-	-	-	-	-	a. Polybenzimidazole// novoloid	+	+	+	*	*	+
	b. FR cotton//aramid	0	0	0	-	*	0	b. Cotton//polyurethane	-	-	-	-	-	-	b. FR aramid//novoloid	+	+	+	*	*	+
	c. Aramid//FR cotton	0	0	0	-	*	0	c. FR paper//PET	-	-	-	-	-	-							
	d. Novoloid/aramid// aramid/novoloid	0	0	0	-	*	0	d. FR cotton//FR cotton	0	0	*	-	-	0							
								e. FR paper//PVC/PVOH	0	0	*	-	-	0							
22. Sealants								a. Polysulfide	-	-	*	*	-	-	Polyphosphazenes	+	+	+	*	*	+
								b. Fluorosilicone	0	0	*	0	-	0							
								c. Viton®	0	0	*	*	-	0							
23. Seat belts	a. Nylon	0	0	0	0	*	0	Nylon/rayon	-	-	*	*	*	-	Polybenzimidazole	+	+	+	+	*	+
	b. Aramid	0	0	0	-	*	0														
24. Seat cushions (foam)								FR polyurethane foam	-	-	-	-	-	-	a. Steel spring/FR batting	+	+	+	*	*	+
															b. Phosphazene foams	+	+	+	*	*	+

Use	Generally Acceptable		Needs Improvement		Possible Future Development	
25. Seat upholstery	a. Aramid	0 0 0 – * 0	a. Wool	0 0 – – – *	a. Polybenzimidazole	+ + + * * +
	b. Aramid/novoloid	0 0 0 – * 0	b. FR wool	0 0 0 – – 0	b. FR aramid	+ + + * * +
			c. Rayon/nylon	– – – – * –		
			d. Nylon	0 – – – * *		
			e. FR cotton/rayon	0 – – – * *		
			f. Nylon/neoprene	0 – – – – –		
			g. FR rayon/novoloid	0 0 0 * * 0		
			h. Modacrylic/aramid	0 0 0 – – 0		
			i. PVC/PVOH	0 0 0 – – 0		
26. Seat trim	a. Polyphenylene oxide	0 0 * * * *	a. ABS/vinyl	– – – – – –		
	b. Polysulfone	0 0 * * * *	b. ABS/polyester	– – – – – –		
			c. ABS	– – – – – –		
			d. PVC-acrylic alloy	0 * * – – *		
27. Thermoplastic parts	a. FR polycarbonate	+ * 0 * * *	a. Bisphenol A polycarbonate	0 * * – * *		
	b. FR PPO blends	0 0 0 0 * –	b. PPO blends	0 0 0 – * –		
			c. FR-ABS	0 – – – – –		
28. Trash can line			Polyethylene	– – – 0 0 –		
29. Wall covering			PVF over PVC film	0 0 0 – – 0		
30. Windows (transparent aircraft enclosures)			a. Acrylates	– – – – * *	a. Epoxy-TMB	* * * * * +
			b. Bisphenol A polycarbonates	0 * * – * *	b. Phenolphthalein polycarbonate	+ + + * * *
					c. Polyarylsulfone	+ + + * * +
31. Window shade assembly	a. FR bisphenol A polycarbonate	0 0 * * * 0	Bisphenol A polycarbonate	0 * * – * *	Furan/glass laminate, FR coating	+ + + * * +
	b. Polysurfone	0 0 * * * 0				
32. Wire insulation	a. Polyimide with fluorocarbon outer jacket	* * + + * +	a. PVC with fiberglass and nylon jacket	* * * – – *	Fluoroelastomer with fiberglass sleeving	+ + + + * +
	b. Silicone-covered fiberglass sleeve	+ + + + + +	b. Polytetrafluoroethylene	+ + + + * +		
			c. Polychlorotrifluoroethylene (as conduit)	+ + + + * +		

KEY:
– = unsatisfactory
+ = good
* = further study needed
0 = satisfactory

3. Endothermic decomposition of the retardant.

4. Degradation of the retardant into free radical acceptors that interfere with flame chain reactions.

5. Formation of a nonvolatile char or oxygen barrier that reduces heat transfer from flame to the polymer.

6. Creation of finely divided particles or solid interfaces that reduce flame propagation by altering the course of the reaction and lead to less reactive radicals.

The development of inherently thermally stable polymers has received much emphasis in attempts to reduce flammability of aircraft materials. In many such polymers there is a high degree of aromaticity permitting participation in high temperature reactions that lead to formation of high residual char.

5.3.3 Applications of Polymers in Aircraft

5.3.3.1 Sidewalls, Ceilings, Partitions, Cabinets, Seats, Etc.

Structures such as sidewalls, ceilings, partitions, cabinets, and seats use a variety of materials and combinations of materials (e.g., polyvinyl chloride polyvinyl fluoride (Tedlar®), polyacrylonitrile/polybutadiene/styrene (ABS), epoxies, polycarbonates polysulfones, aromatic polyamides (Nomex®), phenolic-glass, polystyrene-modified polyphenylene oxides (Noryl®).

Polyvinyl chloride and polyvinyl fluoride are used as coatings over various composite substrates. The choice of polyvinyl chloride is based on its low cost, flammability resistance, durability, and aesthetics. Polyvinyl fluoride is used primarily because of ease of maintenance, including low odor absorption, durability and aesthetic possibilities. Both polymers have the potential for evolution of hydrogen halides HC1 or HF) on exposure to fire. The large areas exposed in these applications enhance the chances of exposure to fire. Although these materials are not probable sources of hazard as "first to ignite" they can become seriously involved under conditions of high heat flux.

Epoxies are used as composite binders and in some adhesive applications. These can be modified by addition of fire retardants and can contribute to smoke production. Fire-retarded compositions may contain halogenated compounds that would constitute an additional source of halogen acid in a fire.

ABS and fire-retarded ABS are used primarily because of their durability and ease of fabrication into complex shapes. With large ignition sources under conditions of high heat flux, the fire-safety characteristics of fire retarded ABS are greatly diminished. Burning ABS produces a large amount of smoke and relatively high amounts of hydrogen cyanide (HCN) and, thus, its use represents a substantial hazard from the fire safety point of view.

Polycarbonates, polysulfones and Noryl® are used for molded parts and some sheet-formed parts. They have a significantly increased degree of inherent fire retardance compared with hydrocarbon polymers, but all burn in high thermal en-

vironments. Noryl® produces relatively large volumes of smoke; polycarbonates and polysulfones produce less. There is no documented specific toxic gas problem, although sulfones would be expected to generate various sulfur oxides.

Many of the disadvantages noted above might be decreased, and in some cases eliminated, by substituting char-forming resin systems such as phenolic and furan resins. These materials are currently available in commercial quantities at moderate cost. Their major disadvantages, relative to the materials presently in use, are poor color characteristics, and the need for more costly fabrication techniques. Development work on fabrication techniques may be rewarding. Color problems might be overcome by the application of suitable coatings. Economic disadvantages of fabrication may be offset in aircraft applications by advantages in fire safety.

5.3.3.2 Elastomeric Foams

While polyurethane-based foams are the only materials available for seat cushions that meet "in-place" cost, comfort, and weight requirements, their flammability and smoke characteristics are unsatisfactory. The fire-retarded versions are more resistant to ignition from small ignition sources but are highly flammable in high-heat flux environments and produce more smoke and potentially more toxic gases than unretarded versions. Although there are few documented cases in which cushioning foams were primary or even secondary ignition source, the large amount (approximately 400 to 2,000 pounds depending on the aircraft) used and its location in the aircraft present a significant potential hazard. Until "safer" cushioning foams or alternate systems of cushioning are developed, every effort should be made to protect cushioning foams from ignition or "cook-off" by design of the system (e.g., multilayered fire-resistant coverings).

Only a few new approaches to developing elastomeric foams that exhibit improved fire safety are being pursued primarily because the most satisfactory approaches to generating materials with low smoke and fire-retardant (high char formation) properties are based on highly cyclic formulas that yield rigid non-elastic polymers not suitable for flexible foam manufacture. The most promising approaches under development appear to be based on inorganic elastomers (i.e., silicones and phosphazene polymers), but these materials need extensive work before they are functionally and economically suitable. In addition, the toxicity of combustion products from phosphazene polymers is essentially unknown and must be studied.

5.3.3.3 Textiles for Cabin Furnishings

Textiles as a class (carpets, draperies, pillows, blankers, upholstery) comprises up to 15 percent by weight of the polymer content in aircraft. The natural fibers (cotton and wool) and the synthetics (rayon, acetate, nylon, polyester, and acrylics) used freely in civilian homes and offices are for the most part readily ignitable and would be *a priori* unacceptable in military and civilian aircraft applications.

Some degree of fire retardance is attainable for most of these fibers by chemical modification (e.g., incorporation of phosphorous, halogen, antimony, transition metals or boron combinations) which generally reduces or eliminates the hazard of ignition by a small source such as cigarettes or matches; in the event of exposure to fully developed fires or high-heat flux conditions, such modifications offer little protection. Some materials that are presently used in a limited way for consumer products provide reduced flammability by virtue of their chemical nature (e.g., phenolics, aromatic polyamides, fiberglass) and should be considered for more extensive use in aircraft where fire safety is a dominant factor.

Some system aspects must be kept in mind when assessing the flammability of fibrous products. For example, thermoplastic fibers (nylon, polyester, acetate) and their flame-retarded versions can resist ignition because of their tendency to shrink and melt away from the ignition source. In order for this phenomenon to play any role, the fibers must not be used in conjunction with nonmelting fibers such as cotton, rayon or acrylic. Polyester/cotton and nylon/rayon blends are examples of hazardous compositions because the thermoplastic behavior of one fiber is "inhibited" by the presence of the nonthermoplastic component. Carpets can be improved with respect to resistance to ignition by utilizing appropriate backcoating materials, e.g., alumina hydrate filler in the backing.

Nitrogen-containing polymers (i.e., acrylics, wool, and nylon) in their natural and flame-retarded versions are known to evolve HCN during pyrolysis and combustion, thus raising concern over toxicity. The aramids (such as Nomex® and Durette®) offer flame resistance characteristics superior to those of nylon and wool but have not been fully evaluated with regard to toxicity problems. The use of phosphorus, halogen and metal oxide treatments to reduce flammability of fibers generally raises questions concerning the potential toxicity hazard in the closed environment of an aircraft cabin and further study of the products generated in burning of fire-retardant fibers is needed. As many other situations, trade-offs must be made for the specific application.

5.3.4 Specific Problem Areas

Approximately 55 percent of aircraft fire reportedly occur in the galleys. The airlines determine the materials used in this area and it should be a prime target for early replacement of flammable polymeric materials. For example, polyvinyl fluoride is used in significant amounts and consideration should be given to substitution of other existing polymers that are less flammable, high char forming, and low smoke producing even if some sacrifice in overall appearance, maintenance and decorative possibilities must be made. Some available char-forming materials should be evaluated for such applications even though fabrication is more difficult.

Improvement in food service procedures (e.g., handling of trash and elimination of on-board cooking also would tend to decrease hazards in the galley area (see Chapter 4). Some of the most flammable materials in aircraft are carried on by passengers, and a rule prohibiting smoking throughout the aircraft would reduce the

hazard (see Chapter 4). The chemical oxygen system that generates oxygen also may represent a serious fire hazard in the passenger compartment in view of the materials surrounding it (see Appendix D).

5.4 Smoke and Toxicity

One of the important parameters to be considered in assessing the flammability characteristics of polymeric materials is the question of smoke. Smoke can be considered part of the fire hazard because it causes panic and may obscure door openings, exit signs, and other means of escape and may prevent rescue by firemen and others; in addition, ingestion of the solid particules and aerosols contained in smoke may be harmful.

Relatively few data are available on the measurement of smoke evolution from materials involved in large-scale fire situations. Some efforts have been made to correlate the results from the NBS smoke density chamber to large-scale aircraft tests. The NBS smoke chamber is designed to examine smoke formation under smoldering or flaming conditions. It is reported that cellulosics produce more smoke under smoldering conditions than under flaming conditions while the reverse may be true for some other polymers (e.g., polystyrene). Many attempts have been made to reduce smoke evolution from burning polymers, but essentially no major reduction has been achieved by adding smoke suppressants to the polymers. Furthermore, some materials that generate relatively little smoke can contribute to the hazard through formation of toxic gases, and the optical density of the smoke gives no indication of toxic production. Attempts have been made to correlate the weight loss of a polymer burning under flaming conditions with the amount of smoke produced and it has been shown that smoke is not an intrinsic property of polymeric materials and is greatly dependent on conditions of combustion.

Toxic products released from burning polymers create an extremely complex set of problems (see Chapter 7). In the combustion of organic polymers, a significant amount of carbon monoxide, a toxic gas, generally is produced. Furthermore, heat flux, ventilation, sample size, and sample design all influence the mode of thermal decomposition and, in turn, the nature and concentration of chemical compounds formed. For example, at low oxygen concentrations some modified aromatic polyamides do not yield benzonitriles while at oxygen concentrations of 21 percent these same polymers reportedly yield significant quantities of benzonitriles. Other materials such as polyvinyl fluoride yield hydrogen fluoride (HF) and carbonyl fluoride (COF_2) in the early stages of a fire, but as these fluoride species are depleted in thermal degradation, the materials evolve entirely different products that may burn vigorously as new species are formed.*

Based on the flammability criteria outlined, the aromatic polyamides, the polyimides, and other thermally stabie materials seem to be durable. Use of fire-

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*Private communication, J. Parker

retardant additives to or modification of these polymers by fire-retarding techniques further decreases flammability but may lead to toxic or otherwise objectionable degradation products. Only by thorough analysis based on test results can one ascertain whether the decrease in flammability brought about by these modifications is beneficial. In considering toxic gas production, all nitrogen-, halogen-, antimony-, and phosphorus-containing polymers and their compositions with other materials are suspect and should be evaluated under a variety of conditions of combustion.

A great deal of concern has been expressed about the potential products of combustion of fluorine-containing polymers alone and in combination with other materials. These products should be carefully analyzed and the interrelationships of all degradation products formed should be considered.

Such toxicological questions must be resolved because they have an important bearing on the actual materials selected for use in aircraft (see Chapter 7). For example, it ultimately may be desirable, if suitable materials become available, to remove from the aircraft cabin all materials that produce hydrogen halides in a fire. This type of situation might require the development of substitute polymers that produce the lowest possible amount of smoke and hydrogen halides and match the performance properties of the material now used. This is a difficult long-range task and one that requires the most sophisticated technological skills.

Similarly, the use of antimony compounds as synergists in enhancing the flame resistance of halogen-containing polymers has not been evaluated in sufficient depth with respect to the consequences on smoke evolution and on the formation of toxic decomposition products. In the case of phosphorous-containing flame retardants, the assumption has been made that the end result is to alter degradation reactions in the solid phase and that volatile toxic compounds usually are not formed. This is an over-simplification and work is needed with regard to the mechanism of flame retardation by phosphorus compounds in specific polymeric substrates, the chemical reaction and transformations of these materials under conditions of burning, and the potential toxicity of volatile phosphorus-containing species.

5.5 Current Research

Table 3 (see Section 5.3.1) in addition to assessing the flammability of materials used for specific application in aircraft interiors, also lists materials for future development. Many of the latter are not only relatively nonflammable but also emit little smoke and toxic gas when exposed to flame. The intention of this section is to discuss current research and development programs including the utilization of materials. Many industrial laboratories are very active in this area; however, details of their work generally are not publicly available at this time.

5.5.1 Fibrous Materials

The recent development of a number of second generation thermally stable

polymers, e.g., polybenzimidazoles (PBI), aramids, phenolics, polybisbenzimidazobenzophenathroline (BBB), from which relatively non-flammable fibers can be made is the first step in providing replacements for the flame-retardant-treated wool, rayons, acrylics, and Nomex® currently used in aircraft interior applications.

Even though the latter group of fibers are an improvement over the previous ones, there are still unresolved problems. A major one is the unknown but potential toxicity of decomposition products when the fibers are exposed to high heat fluxes or flames. Similarly, the smoke yield as well as the toxicity of decomposition products are unknown for most of the second generation, thermally stable polymeric fibers. Lack of commercial availability of PBI and BBB are major concerns of the Department of Defense and others who might want to use the promising materials. However, because these satisfy the need for reduced flammability, current efforts are directed toward the development of methods that can be used to assess toxicity and smoke obscuration when the materials are burned. Efforts sponsored by NASA are directed toward identifying the specific toxic gases that cause fatalities in animals exposed to the products formed during heating and combustion. The quantity of gas and time required to cause death are the criteria of importance in these programs. In addition, the dangers of toxic gases from burning cabin materials is being studied by the FAA (National Aviation Facilities Experimental Center). Selected toxic combustion gases are being measured using 75 representative cabin materials from a wide-bodied jet cabin (B-747, DC-10 and L-1011). The eventual application of this work is to provide the data base for an FAA toxic combustion gas regulation.* The synthetic fiber producers continue efforts to develop polyester fibers with reduced flammability singly or in blends with thermally stable fibers which will conform to current and anticipated FAA regulations for fire resistance, smoke emission and toxicity.

The chelated polymers represent a new class of materials that can be formed into fibers having a limiting oxygen index (LOI) of up to 52. These polymers, which can be spun into fibers and readily chelated, give products whose properties can be controlled by the metal and conditions used for chelation. The fibers are reported to have excellent fire resistance, i.e., they carbonize and form chars without total consumption, thereby retarding the propagation of the fire.

New polyamides, polysulfonamides, wholly aromatic heterocyclic polymers, and silicon-containing aromatic polymers also are being studied as fiber-forming polymers that exhibit thermal stability. The Army Materials Laboratory has initied the preparation of sufficient quantities of these polymers for fiber-spinning trials. These approaches are clearly long-range efforts and some years must elapse before applications of the materials can be considered.

Of short-range interest is the improvement of currently available flame-retardant fibers being studied extensively in government laboratories and industrial organizations. Programs currently in progress are focusing on:

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*A preliminary FAA report on 15 materials, including results of exposing animals directly to the combustion products is being prepared.

1. The study of blends of two or more available fire-retardant fibers in order to optimize properties of nonmelting textiles (e.g., Nomex® Kynol®, PFR rayon, modacrylics) in laboratories of the Air Force and the Navy as well as commercial fiber producers.

2. Development of new chemical systems for fire-retardant finishing of textiles made from natural fibers (in the laboratories of the chemical industry and the producers of cotton and wool).

3. Development of modified synthetic fibers in which flame resistance is obtained by incorporation of appropriate flame retardants during the fiber manufacturing process (rayon, acetate, and polyester products).

4. Study of flame resistance in blends of polyester with cotton (program sponsored by the National Bureau of Standards through the Experimental Technology Incentives Program).

The last of these, materials intended primarily for apparel applications, is included here to indicate the scope of ongoing research in fiber and fabric flammability. As the results of these studies are published, the information will be available to improve fire safety in aircraft.

5.5.2 Plastics and Composites

The flammability and potential for generating smoke and toxic gases, of plastics and composites currently used in commercial aircraft as paneling, overhead baggage racks, seat frames, etc., are the subject of study by both the government (NASA) and the aircraft companies. A complex composite structure used in many aircraft consists of acrylic ink-printed polyvinyl fluoride film on fiberglass-epoxy sheets adhered to Nomex® honeycomb with a fiberglass-epoxy panel. As this structure burns, it emits copious quantities of smoke and gases that may be toxic. These structures are being thoroughly characterized so that further development programs aimed at replacing the components that contribute the most to flammability and toxicity can be established. Efforts to reduce the rate of flame spread accross panels of this type are included in the scope of current programs. To replace the PVF film, aromatic polycarbonates of bisphenols are being studied by NASA since films of this type offer improved properties such as low smoke and better fire resistance. In a related effort, NASA is conducting investigations aimed at the identification of specific chemical species emitted during heating and/or burning of PVC films and the toxicity of the products.

Typical composite panels, singly and adhered to Nomex® honeycomb, are the subject of a joint Air Force Army flammability study. Intended as candidates for application in aircraft and helicopter structural parts, panels composed of graphite-fiber-reinforced polyimides and graphite-fiber-reinforced bismaleimides are included in the study. Preliminary data have demonstrated the need for improved fire retardance in the current epoxy resin matrix systems and in the adhesives used to bond multilayer structures (fiber-reinforced plastic matrix panels to Nomex® honeycomb) to achieve increased time before delamination occurs.

Attention must be given to the resin systems used for aircraft application to attain the degree of nonflammability and nontoxicity required. Presently research efforts are directed toward the development of:

1. Furan Resin systems
2. Unsaturated polyester resins
3. Phenolic resin systems
4. Isocyanurate foam systems
5. Thermally stable aromatic polyesters
6. Phosphonitrilic polymers and thermoset resins
7. Polyimide and bismaleimide resin systems
8. Polyquinoxaline resins

5.5.3 Elastomers and Sealants

The liberation of copious amounts of smoke and gases (e.g., HC1, CO, and nitrogen oxides by elastomers such as polyvinylchloride/nitrile rubber blends when exposed to heat and fire has led to a program sponsored by the Navy (Naval Ship Research and Development Center) and the Army (Materials and Mechanics Research Center and the Natick Laboratories). The major goal is to develop the phosphazene polymer system into elastomeric forms that can be used as thermal insulation and electrical cable jackets. The elimination of halogen compounds as fire retardants is a primary goal since these materials have a history of yielding corrosive or toxic gases when exposed to heat and/or fire.

Studies to develop polyphosphazene materials suitable for fabricating dipped parts have been initiated. Slabs of polyphosphazene rubber are being evaluated by the Army Materials and Mechanics Research Center to assess environmental aging effects.

NASA (Ames Research Center) and the Air Force (Materials Laboratory) have undertaken a program to develop nonflammable elastomeric materials for a broad spectrum of aircraft applications requiring reduced flammability. The most promising polymer systems studied are polyphosphazenes. Prototype cushions have been prepared for flammability and toxicity investigation. In a related effort NASA (Ames Research Center) has initiated a program to replace semi rigid urethane foam, used as insulation, with low-density foams based on the polyimides and polybenzimidazoles.

5.5.4 Transparent Materials

The polymeric materials currently used in aircraft windows are flammable and yield toxic gases, but durability, including abrasion resistance, is satisfactory. Although the epoxy-trimethoxyborane systems are resistant to ignition and are easily extinguished, they smoke extensively and yield toxic gases. In a program sponsored by NASA (Ames Research Center) and the Air Force (Materials Laboratory) emphasis is being placed on the development of polyarylsulfones and aro-

matic polycarbons. Preliminary tests have confirmed reduced flammability, smoke emission, and toxic gas yield. Fabrication of optically clear panels in aircraft window dimensions (including crew compartment windows) has been initiated so that both flammability and actual use conditions can be simulated; however, fabrication is, at present, difficult.

5.5.5 Thermal Insulation

An effort has been initiated by NASA to use a replacement material for the fiber glass batting now used as insulation on commercial aircraft. The objectives were to find materials that offered weight and acoustical properties equal to those of the standard fiber glass insulation but that provided a fire barrier against an external fuel-fed crash fire. Many materials were evaluated for acoustical and thermal behavior and two were found to be promising: Fiberfrax®, a product of the Carborundum Company, was acceptable acoustically and thermally, but was far too dense. The other material, a lightweight asbestos foam manufactured by Rex Asbestwerke of West Germany, also was good acoustically and thermally but was unacceptable because of the potential health hazard of asbestos particles. A lightweight Fiberfrax® foam structure, similar to that of the asbestos foam was developed by the Carborundum Company. To date, lightweight samples with suitable thermal properties have been fabricated; however, the material has failed to meet the acoustical requirements. Further development is being initiated to improve acoustical properties by blending fiber glass fibers into the foam structure or by making a laminate of the Fiberfrax® foam and the standard fiber glass batting. In addition, preliminary evaluation has been conducted by the Air Force Systems Command and Carborundum Company to determine the feasibility of replacing fiber glass batting with Kynol® (crosslinked phenolic fiber batting.

5.5.6 New Polymer Development Concepts

NASA (Ames Research Center) has shown that the char yield (Y_c) or ash residue of a polymer is a function of the molecular structure of the polymer – i.e., in many structures the char yield is directly proportional to the number of aromatic equivalents per gram of polymer. The char yield has been further shown to be related to the measurable combustion properties of the polymer exposed to a fire.

Flame spread, smoke production, flammability, and relative toxicity are all decreasing functions of the char yield and, hence, are related to the molecular structure of the polymer. Rather than use fire-retardant additives may increase smoke and toxicity, more inherently thermally stable polymers and methods of processing compounds into usable materials are being sought.

NASA is studying the use of integrally woven core and face sheet structures of nondegrading fibers. These structures are impregnated with bismaleimide or polybenzimidazole resins. Some are filled with isocyanurate, polybenzimidazole or polyquinoxaline foams for added strength and insulation. Surfaces will be coated with char-enhanced polycarbonate films bonded on by thermally stable adhesives.

It is expected that these composite structures not only would be resistant to mild or severe ignition threats but also would provide thermal protection of occupancy areas from fires of external origin. The current development of these panel structures also includes consideration of multifunctional properties, such as acoustical attenuation thermal insulation, and secondary load carrying characteristics. The higher cost and increased weight of the material would require an in-depth trade-off analysis.

An important fire safety parameter of a material is the propensity for flashover. Laboratory studies are being conducted at the National Bureau of Standards under a Federal Aviation Agency/National Bureau of Standards interagency agreement to study the flashover phenomenon. (Efforts in this area, with repsect to urethane foam seat cushions are described in FAA Report No. FAA-RD-73-46.

Polyisocyanurate foam has twice the char yield of a comparable urethane and has vastly improved thermal properties. Polybenzimidazole foam has a char yield nearly four times that of urethane and exhibits almost zero flame spread, zero smoke and a limiting oxygen index of 70.

Other materials species can be fire rated in a similar manner. Bismaleimide resin for laminating (Y_c=50%) has much improved properties over polyester (Y_c=0∿10%) or epoxy (Y_c=∿20%) but not as good as PBI resins (Y_c=80–90%). Acrylates (Y_c=∿0) in use for window materials can be fire-improved by replacement with special cured epoxies or possibly by molecularly tailored polycarbonates. These char-enhanced polycarbonates may offer solutions as fire-safe thin films to replace Tedlar® and acrylates and for replacement of electrical insulation (see Sections 5.5.4 and 5.5.2).

5.6 Conclusions and Recommendations

Conclusion: Aircraft safety is the result of several factors operating in concert; polymeric materials of construction represent only one facet. Fire prevention, detection, and control and the use of fire-resistance materials must be considered as parts of the system and the effect of improvement in other areas on the materials situation must be assessed. *Recommendation:* Research and development programs focusing on thermal protection methodology and on hardening the aircraft fuselage against the external fire threat should be extended. Detector and extinguishment systems should be utilized more extensively to decrease the risk of polymeric material flammability.

Conclusion: Many of the polymeric materials used in commercial and military aircraft are deficient from a fire safety point of view. Better materials are available for some purposes and new materials not yet commercially available would be acceptable for other applications; however, there are many areas for which there are no completely suitable materials. Informed trade-offs therefore must be accepted. *Recommendation:* Methods for risk and trade-off analysis should be developed and employed in materials selection. It should be required, when practical, that existing

polymeric materials be replaced with improved materials when it is established that the risk can be decreased significantly.

Conclusion: Meeting existing fire safety regulations is done in the context of economic, serviceability, and aesthetic guidelines, and the use of available improved materials could be accelerated if regulations were more stringent. *Recommendations:* Means to stimulate acceleration of commercial development and availability of advanced materials should be developed.

Conclusion: New test methods are needed to guide materials development and selection. The effects of smoke, heat, and toxic products of pyrolysis are particularly important but have only recently begun to receive attention in materials selection. Combinations of polymeric materials also have more adversely under fire conditions than predicted by evaluation of individual components. *Recommendation:* More meaningful flammability tests and methods of evaluation should be developed to assist in materials development and choice. The toxic hazard from pyrolysis and combustion products of the polymeric materials used in aircraft should be defined and tests and guidelines for evaluation of the hazard developed. Knowledge of the relationships of polymer structure and fire environments to the nature of pyrolysis and combustion products of polymers and combinations of materials should be increased.

Conclusion: Fire safety research on polymeric materials supported by government and industry is fragmented and difficult to assess because of poor information exchange. The division of responsibility for materials selection between airframe manufacturers and aircraft operators creates further problems. *Recommendation:* Fire safety related materials research and development programs should be better coordinated, and sound mechanism for dissemination of information from such programs should be developed. The split responsibility for materials selection and design between aircraft manufacturers and aircraft operators should be resolved.

Conclusion: Materials carried on board by passengers contribute significantly to the fire hazard and load. *Recommendation:* The hazard of carry-on materials should be defined, and more stringent fire safety regulations for in-flight and ramp conditions, particularly as they relate to the carry-on fire load, should be developed and implemented.

Conclusion: The fire safety of cabin interiors can be improved by the selection of currently available char-forming materials, although improvements in fabrication methods also are required. Among the specific areas in need of attention are the galleys and lavatories (where a major portion of the fires start but which can be improved in terms of threat of ignition, flame spread, and smoke and toxic emissions); the flame-retarded epoxies used in wall composites (which can be the source of significant quantities of smoke); the neoprene and urethane-coated nylon fabrics used in life vests, life rafts, and emergency slides (which perform unsatisfactorily in terms of ease of ignition, flame spread, and smoke and toxic gas emission); the polyurethane foam, especially flexible foam, (which is deficient in many fire safety aspects); the carpeting used in vertical position as a decorative material (which

introduces an unnecessary fire hazard); and the polyvinyl fluoride covering used over large areas of many of the interior walls of many aircraft (which represents a potential source of smoke and toxic gas during pyrolysis or combustion). *Recommendation:* The fabrication cost of large complex parts from char-forming materials should be lowered. Galley and lavatory areas should be fire hardened. The fire hardness of the existing polyurethane foam-based seating systems should be improved through design, construction, and selection of covering materials. A fire safe replacement for existing polyurethane foam cushioning should be developed. Known hazardous textile materials (e.g., cotton/rayon blends) used in some aircraft interiors should be replaced with available improved materials. Fire-safe coated fabrics should be developed for use in life vests, life rafts, and emergency slides. The use of organic fiber carpets in a vertical position should be eliminated. The fire safety of the overhead duct insulation systems should be improved through design and materials choice. The fire safety of wall and ceiling panels should be improved through materials choice and new materials should be developed.

5.7 References

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FAA Report, FAA-RD-73-46

CHAPTER 6

TEST METHODS, SPECIFICATIONS, AND STANDARDS

6.1 Introduction

One major element of fire safety lies in the choice of materials and their usage within the system by the designer. The designer's knowledge about materials is based on the results of tests embodied in specifications and standards upon which he can rely. This chapter presents an enumeration and evaluation of currently used test methods and specifications in relation to other facets of fire safety covered in other chapters of this volume and describes the historical development of improved tests for crew/passenger compartment materials.

6.2 Regulations and Requirements

6.2.1 Civil Aircraft – Federal Aviation Regulations

The following Federal Aviation Regulations issued by the FAA, under Title 14, Code of Federal Regulations (14CFR), Chapter 1, prescribe the fire protection test methods, specifications, and standards applicable to the certification of new aircraft engines:

Part 23 – Normal, Utility, and Acrobatic Category Airplanes (General Aviation)
Part 25 – Transport Category Airplanes (Air Carriers)
Part 27 – Normal Category Rotorcraft (General Aviation)
Part 29 – Transport Category Rotocraft (Air Carrier)
Part 33 – Aircraft Engines

Fire protection requirements applicable to aircraft operation are included in the following FAR:

Part 91 – General Operating and Flight Rules
Part 121 – Domestic, Flag, and Supplemental Air Carriers
Part 127 – Scheduled Air Carriers with Helicopters
Part 135 – Air Taxi Operators and Commercial Operators of Small Aircraft

6.2.2 Civil Aircraft Fire Protection Requirements

The aircraft certification of airworthiness standards pertinent to the fire protection requirements for compartment interiors are described in FAR* 23.853, 25.853, 27.853 and 29.853. The cargo and baggage compartment fire protection requirements are specified in FAR 25.855, 27.855, and 29.855. The fire protection requirements for insulation on electrical wire and cable installed in the fuselage of

*Federal Aviation Regulation.

transport airplanes are specified in FAR 25.1359. FAR 23.1183, 25.1183, 27.1183 and 29.1183 describe the fire protection requirements for powerplant flammable fluid lines incorporated as part of the engine installation while FAR 33.18 refers to flammable fluid lines incorporated as part of the engine itself.

The aircraft operation fire protection requirement in FAR Parts 121, 123, 127, and 135 refer to the applicable certification airworthiness standards. Upon the first major cabin overhaul or refurbishing, FAR 121.312 specifies that the crew and passenger compartment materials must be replaced with materials that meet the flammability standards adopted in 1967 if the application for certification of the airplane was filed prior to May 1, 1972. If the date of application for certification was on or after May 1, 1972, the material must meet the flammability standards adopted in 1972. The 1967 standards are described below in Section 6.3.1.1 and the 1972 standards in Section 6.4.1.1. Operators of large aircraft under FAR 123 also must comply with the FAR 121.312 requirements.

6.2.3 Military Aircraft Fire Protection Requirements

Fire protection requirements for military transport aircraft are derived primarily from requirements imposed by the FAA on materials intended for commercial transport type aircraft. In addition to incorporation of the FAA regulations for fire protection into the overall aircraft protection envelope requirements, specific modifications are incorporated depending on the aircraft system being developed. In AFSC 1–6 System Safety Design Handbook, and AFSCM 80–1, Handbook of Aircraft Designs, military (MIL) specifications and specific additional requirements are included that can be made applicable to specific aeronatical systems.

Requirements for fire-retardant materials in combat aircraft (fighters, bombers, etc.) are more difficult to define since only small quantities of polymeric materials are utilized. When practical, the requirements of AFSC 1–6 are applied to ensure incorporation of the most fire resistant polymeric materials. However, deviations are extensive. Some problems develop from the utilization of the lowest cost material available.

Advanced Warning Aircraft Control System (AWACS) aircraft require special equipment and furnishings to permit the crew to operate at peak performance. In some cases these furnishings and equipment are made of flammable materials. Review of the characteristics of these aircraft from a fire safety standpoint appears desirable.

Helicopters present separate problems in establishing requirements to overcome flame damage and destruction in the case of accident. The close proximity of fuel and engine to the crew has precipitated utilization of a different type of fire protection system. Requirements have been established to incorporate a crashworthy fuel system that will prevent fuel spillage in case of an accident even though the engine breaks away from the aircraft. These installations have been very effective and have markedly reduced fatalities due to post-crash fire. U.S. Army efforts in this regard are noteworthy for positive results obtained.

6.3 Historical Development of Improved Tests for Crew/Passenger Compartment Materials

6.3.1 Transport Aircraft

The United States commercial aircraft manufacturing industry dominates the world market for commercial transport aircraft. Jet transport aircraft used by airlines all over the world are for the large part manufactured by the three major U.S. manufacturers: Boeing (707, 720, 727, 737, 747), McDonnell-Douglas (DC-8, DC-9, DC-10), and Lockheed (L-1011). The safety record of U.S. manufactured aircraft is impressive; the Boeing 707 flew 1.5 billion passenger miles before the first fatal crash, and the Boeing 747 flew 13 billion passenger miles before its first fatal crash. Much credit for this safety record is due to the efforts of the aircraft manufacturers and the FAA.

Material flammability standards and test procedures established in 1947 required wall and ceiling linings, upholstery covers, floors, and furnishings in crew/passenger compartments to be flame-spread resistant (maximum average horizontal burn rate of 4 inches/minute over a 10-inch length). Materials used in the construction of cargo or baggage compartments were also required to be flame-spread resistant. The 1947 standards substantially reduced the cabin fire potential at that time by eliminating the use of cellulose-nitrate-doped fabric that had an almost explosive horizontal burn rate of about 20 inches/minute.

In 1963, prompted by a series of ground fires in the cabins of several transport aircraft, Marcy, Nicholas, and Demaree* investigated the flammability and smoke characteristics of about 100 interior materials that complied with the 1947 standards using the test facilities of the National Bureau of Standards. This investigation disclosed that the 1947 test procedures were not suitable for materials other than fabrics and that materials were available which were self-extinguishing within 15 seconds after removal of the test flame in a vertical test. Marcy also investigated the ignition and burning characteristics of interior materials that met the 1947 flame-resistant standards by conducting full-scale cabin interior fire tests during the period 1962-1964. These tests revealed that a small fire allowed to propagate could culminate in a flash fire and ceiling temperature of 1,600° F (870° C) with little or no warning.

Following the jet transport accident at Salt Lake City, Utah, on November 11, 1965 in which 43 passengers perished due to effects of the post-crash fire in the cabin, the FAA expanded the test program under way at the National Aviation Facilities Experimental Center (NAFEC) to provide further data for improving the 1947 flammability standards. The FAA, Marcy, and Johnson reported flammability test data on July 1968 on no less than 150 interior materials that included advanced materials such as high-temperature polymers (e.g., aromatic polyamide, polyimide, bisphenol A polycarbonate, polysulfone, and the fluorocarbons). The

*See references pp. 102, 103.

FAA test program complemented the test program of the Aerospace Industries Association (AIA) in 1966 and 1967 in which thousands of materials were investigated. The results of these test programs indicated that a substantial increase in the fire retardance of materials had been achieved with the development of new high-temperature plaatics and the use of flame-retardant additives to the more conventional plastics. Full-scale cabin interior fire testing in the AIA program demonstrated that the improved materials effectively provided a lower rate of temperature rise in an airplane cabin under moderate fire conditions. It should be noted that material choice and usage contribute more to fire safety in the non-fuel-fed "moderate" fire than in an intense fire where material choices are overridden by the hostile environment. These data supported drastic improvements in the FAR Part 25 aircraft certification airworthiness standards that were adopted in 1967. The 1967 standards established flammability criteria for cabin and cargo compartment interior materials as defined by the vertical test and specialized composite horizontal test for cabin materials as well as the horizontal test for cargo compartment lines. The vertical flame test (self-extinguishing, 12-second ignition, 8-inch burn length) applies to ceiling and wall panels, carpets, upholstery, and other cabin materials. The horizontal test (15-second ignition, 4-inch burn length) is conducted in addition to the vertical flame test and applies to materials tested vertically as a fabricated unit. The horizontal "flame-resistant" test (burn rate of 4-inches/minute 15-second ignition) applies to window frames, windows, ducting, small parts, and all other materials not required specifically to be tested vertically (several small items such as wire insulation, black boxes, and pulleys are excluded from flammability tests). The 45-degree test (self-extinguishing in 15 seconds, 10-second glow time, must not penetrate material in test time) applies to liners of all cargo compartments except those in which a fire would be easily discovered by a crewmember while at his station and where each part of the compartment is easily accessible in flight.

As a result of new material developments and availability of improved materials, the 1967 standards were upgraded in 1972 to include two horizontal tests (2.5-inch/minute and "flame-resistant") for cabin materials, the 45-degree "fire-resistant" test for cargo compartment liners, and the 60-degree test for wire insulation. The 1972 standards are fully described in Section 6.4.1.1. The 1972 standards covered virtually all cabin materials, notably including cabin furnishings and thermoplastics. In the material flammability test programs, many of the plastic materials were found to produce smoke and toxic gases that, in sufficient amounts, are lethal. During 1966 to 1968, the FAA contracted with NBS to measure the smoke and toxic gas emission of about 140 interior materials. These data were collected in the NBS smoke density chamber under conditions of radiant heat or combined radiant heat plus open flame exposure to test materials. Smoke was measured continuously throughout the test while gas samples were taken only when the smoke peaked out. The FAA, recognizing the importance of the additional hazard of toxicity from products of combustion and/or pyrolysis, in July 1969 issued

Advanced Notice of Proposed Rule Making No. 69-30, soliciting comments regarding the feasibility of establishing limits for smoke emissions from burning or smoldering cabin materials. The general response indicated that the state of the art was relatively undeveloped. It was recommended that research should continue on both smoke and toxic gas emissions and that standard smoke evolution criteria and standards measurement methods for combusted and pyrolyzed polymeric materials, according to usage, should be the principal targets for this research. Use of a quantitative approach to the kinetics of energy and mass transfer also was recommended.

In 1972, the FAA contracted with the Lockheed-California Company to conduct material smoke tests in a wide-body cabin mockup and investigate the degree of correlation with the results of the NBS smoke density chamber test. In this program, Lopez found fair to good correlation between the NBS smoke density chamber test data and cabin mockup smoke test data. In another FAA-sponsored program, Einhorn conducted a physiochemical study of the parameters that govern smoke emission of cabin materials. In this same program, Einhorn, Kanakia, and Seader evaluated the flammability characteristics and thermal degradation of urethane cellular plastics used in aircraft cabins. Paabo and Comeford of NBS developed laboratory equipment under FAA contract to assess the flash fire potential of flexible polyurethane foam used in aircraft cabins and to obtain data on the composition of gases producing flash fires. Flash fires were not produced in this laboratory model with the smoke filtered out. It was concluded that additional research was required to better define the material properties and environments causing flash fire in view of uncertainties about some of the data.

Of crucial importance is the toxicity of combustion products. Blood samples from the victims of the accident and postcrash fire that occurred at Anchorage, Alaska, November 27, 1970, were analyzed for the first time for the presence of cyanide. Cyanide analyses also were performed on the victims of accidents in Chicago, Illinois on December 8 and December 20, 1972. These results were not conclusive. Further toxicological work is needed.

Current programs are being carried on by the FAA, NASA, Air Force, and other researchers to supplement the toxic gas emission data obtained earlier. A major objective of the FAA is to establish a reasonably inexpensive analytical technique for continuously measuring the levels and emission rates of significant toxic gases released by burning materials so that the materials can be graded in terms of toxicity and evaluated in terms of hazard. The materials being tested by the FAA are the same as those commonly employed in wide-bodied commercial aircraft. They are also being compared and measured during combustion in the NBS smoke density chamber as well as in a tube furnace for their release of smoke and toxic gases. This study involves animal tests and is expected to provide a ranking of the tested materials in order of their relative toxicity. Although colorimetric detector tubes have been used for accomplishing this task, the results obtained by this

technique will be supplemented and compared with data collected by other analytical methods (e.g., specific ion electrodes, infrared spectrophotometry, gas chromatography).

The chemical character and the analytical determination of the products of combustion or smoldering of plastics are discussed in Chapter 7, and the importance of establishing test methods capable of furnishing the required data with sufficient precision and accuracy can only be repeated here. The necessary sensitivity, precision, and accuracy remain to be determined by the research, including animal correlation, currently under way.

NASA Johnson Space Center at Houston and Ames Research Center at Moffett Field and their contractors are conducting materials and animal studies and full-scale tests to develop cabin materials that possess improved flammability, smoke, and toxic gas emission characteristics. Testing sponsored by the Society of the Plastics Industry to obtain toxic gas emission data also is under way at NBS and Southwest Research Institute. Testing also is being done at the University of Utah, Factory Mutual Laboratory, Underwriters Laboratory, Illinois Institute of Technology Research Institute, Army Laboratories, and Lawrence Livermore Laboratory.

It is believed that the current flammability self-extinguishing requirements for interior materials do assist in controlling cabin fires when prompt extinguishing action is taken. Materials meeting these requirements represent the current state of the art for reducing the fire propagation hazard that has long been considered most important in a post-crash situation. An Advanced Notice of Proposed Rule Making is currently being processed with the FAA which ultimately will solicit public comments concerning the establishment of a material toxicity standard. There is a problem establishing such standards since the technical data base on toxicity for short time exposure to products from total combustion is relatively undeveloped. This is an area in materials technology that warrants and is receiving increased attention. In addition, large-scale tests and actual accidents have shown that smoke and gases from smoldering and burning materials can fill the upper part of the cabin and, when ignited, create intense, short-duration flash fires. The cabin fire hazard cannot be fully controlled until means for controlling the flash fire phenomenon are developed and incorporated in materials evaluation criteria. Suitable tests are needed to be developed.

Although military aircraft are designed using the safety standards described in both Air Force and FAA regulations, the continued problem of fires, especially in transport-type aircraft, demonstrates the lack of adequate fire-resistant materials. In the 5-year period ending December 1973, 27 negligible-impact transport aircraft accidents involved fire; burns accounted for 93 fatalities and 63 serious injuries. The materials used did little to provide adequate protection for the crew and passengers.

Other incidents have occurred that demonstrate the inadequacies of currently used materials. Typical of these incidents are two separate cases which polyurethane aircraft seats used in the C-5 were ignited while in storage and caused exten-

sive damage to stored equipment. In addition, the policy of retrofitting interiors of transport-type aircraft by individual Air Force bases has resulted in many materials being used (e.g., carpeting, drapes, seats, wall covering) without determination of fire resistance. The lack of a handbook that not only describes the test procedures for flammability, but also specifies materials that do meet the Air Force and FAA requirements has increased the difficulty of personnel responsible for retrofitting aircraft to determine fire resistant materials suitable for aircraft interiors. Most materials used in retrofit programs are generally off the shelf and are chosen primarily for appearance and low cost rather than fire resistance or minimal smoke generation.

A major effect in the Department of Defense has been to provide greater protection to the individual by means of fire-resistant or non-flammable clothing per Test Method 5904. Recently, the Air Force initiated an across-the-board retrofit of seat cushion covers and cushions. Similarly, the continued incorporation of the crashworthy fuel system into U.S. Army helicopters may reduce the requirements for more fire-resistant materials in these modified systems.

6.3.2 Modified Fuels

When conventional liquid fuel is ignited an intense fire may be produced that can enter the passenger compartment and ignite the interior materials. Efforts are under way in the United States by the FAA and the Army, and in the United Kingdom at the Royal Aircraft Establishment, to determine the fire-reduction effectiveness of polymeric fuel additives that can eliminate combustible fuel mist by imparting viscoelastic characteristics to released fuel to create a coarse spray of large droplets instead of the fine spray mist usually created.

The flammability characteristics of these anti-mist modified fuels are being assessed using various test methods. While all test results cannot be correlated because the test conditioners differ, they generally indicate that several high-molecular-weight anti-mist polymeric fuel additives, such as polymethylmethacrylate, provide for reduced total surface area and rate of vaporization, which prevents flame propagation through the spray. Testing is currently in progress to establish the interrelationship between fire-reduction effectiveness and additive concentration, fuel temperature, fuel condition (pumped and non-pumped), fuel quantity released, airflow velocity, as well as the location and magnitude of ignition source and to thoroughly define the behavior of the modified fuel in a survivable crash.

A full-scale airplane crash test will be conducted to demonstrate the safety benefits of modified fuel if current efforts establish that use of the modified fuel conditions offers reasonable assurance that the probability and severity of post-crash fire will be reduced in a survivable crash environment. The successful completion of the flight test program will emphasize the need for development of a suitable laboratory test method. This laboratory test method would be included in a modified fuel specification, as a safety test requirement, which modified fuel must meet before being approved for use in civil and military airplanes.

6.4 Specifications and Standards

6.4.1 Interior Materials

6.4.1.1 Transport Category Airplanes

Materials are required to be self-extinguishing as defined by standards specified in FAR 25.853, 25.855, and 25.1359. The test methods for showing compliance with these standards (described in Appendix F to FAR Part 25, Chapter 4) are:

1. Vertical Test, Federal Test Method Standard 191, Method 5903

   For ceiling panels, wall panels, galley structures, etc. – apply 1550°F (849°C) flame for 60 seconds. Burn length not to exceed 6 inches. Flame time after removal of test flame not to exceed 15 seconds. Drippings from the test specimen may not continue to flame for more than an average of 3 seconds after falling.

   For carpets, draperies, cushions, upholstery, etc. – apply 1550°F (850°C) flame for 12 seconds. Burn length not to exceed 8 inches. Flame time after removal of test flame not to exceed 15 seconds. Drippings from the specimen may not continue to flame for more than an average of 5 seconds after falling.

2. Horizontal test, Federal Test Method Standard 191, Method 5906

   For acrylic windows, seat belts, signs, etc. – apply 1550°F (850°C) flame for 15 seconds. Average burn rate not to exceed 2.5 inches/minutes (4 inches/minute for small parts).

3. 45 degree test

   For cargo and baggage compartment liners – apply top one third of 1550°F (850°C) flame for 30 seconds. Flame may not penetrate the specimen. Flame time after removal of test flame not to exceed 15 seconds.

4. 10 degree test

   For insulation on electrical wiring – apply 1750°F (960°C) flame for 30 seconds. Burn length not to exceed 3 inches. Flame time after removal of test flame not to exceed 30 seconds. Drippings from the test specimen may not continue to flame more than an average of 3 seconds after falling.

The FAR Part 25 standards represent the minimum acceptable level for aircraft certification. Since FAA crashworthiness criteria advise aircraft manufacturers to use the "best available material," material qualification test standards specified by the aircraft manufacturers are sometimes more stringent than those specified in FAR Part 25.

6.4.1.2 General Aviation Airplanes and Helicopters

Prior to November 7, 1973, the interior materials in general aviation airplanes in non-smoking areas were required to have not more than a maximum average horizontal burn rate of 20 inches/minute. In smoking areas, they were required to have not more than a maximum average horizontal burn rate of 4 inches/minute over a 10-inch length. Amendments to the FAR Part 23 aircraft certification airworthiness standards were adopted on November 7, 1973; these delete the option to prohibit smoking and allow flash-resistant materials. All interior materials in new aircraft must now be at least flame-resistant if the date of application for certification of the aircraft is after November 7, 1973. The option to allow flash-resistant materials and prohibit smoking or incorporate flame-resistant materials and allow smoking was retained for helicopters.

6.4.1.3 Military Aircraft

Many test methods are used in determining the ability of polymeric materials to resist burning. Many materials specifications still do not contain a requirement for fire resistance. The types of flammability test currently in use by material type are listed below:

1. Rigid Plastics (primary polyamides) – Method 2021 Federal Test Method Standard 406.
2. Rubber Components, Foam – Exposed to a C-C-91, Class B candle for 1 minute.
3. Molding and Potting Compounds, Polyurethane – Cylinder of compound wrapped in No. 16 wire with 55 amps input for 2.5 minutes.
4. Sealing Compounds – Method 2021, Federal Test Method Standard 406.
5. Adhesives, Fire-Resistant – Vertical Flame Test (no specific method) for 5 seconds.
6. Insulating Compound Molded, Electrical – ASTM D-876; Method 2021, Federal Test Method STandard 406.
7. Carpets – Flame test similar to tunnel test except 2 meker burners used with an airflow of 650 ± 10 cc/minute.
8. Drapes, Upholstery, etc – Method 5902, 5903, 5910, Federal Test Method Standard 191.

6.4.2 Powerplant Flammable Fluid Lines

Flexible hose assemblies (hose and end fittings) made from materials such as polytetrafluoroethylene, which carry flammable fluids and are subject to engine fire conditions, must be at least fire resistant as defined in Technical Standard Offer TSO-C53a.

6.5 Adequacy of Materials Testing

Those concerned with the assessment of fire safety associated with design

choice of materials need to speak a common language and that language is essentially one of flammability test methods. A test method, like the words of any language, must be used in the proper context. As fire research sophistication increases, so should the degree of systematic approach to test methods.

To a person unfamiliar with the details of fire tests, it would appear that the material that exhibits superior performance over another in one fire test would exhibit superior performance in any other. Unfortunately, this is not always the case since relative performance can vary considerably depending upon the test used.

No single fire test and perhaps no combination of a limited number of fire tests can predict the behavior of materials under all possible conditions of fire exposure, and economic factors prohibit the performance of all fire tests that could be relevant to all possible fire scenarios. Therefore, fire tests can and should be classified according to intent, and on this basis can be divided into the following three groups:

1. Laboratory research and developmental tests that are designed to obtain information on the basic properties of a material or combination of materials and on the effects of different variables on those properties. Such basic properties may be considered to include ignition temperature, oxygen index, and heat of combustion.

2. Pragmatic tests that are designed to simulate the anticipated conditions of use and that are intended to serve as standards on which specifications may be based. Examples include the federal flammability standards for carpets and rugs, matresses, upholstered furniture, and children's sleepwear. Tests that are pragmatic in origin usually were not developed from a scientific basis, and any correlation between the results of research, pragmatic tests, and full-scale fire tests should be considered fortuitous.

3. Full-scale or large-scale tests that are designed to reproduce actual fire scenarios under controlled and measured conditions. Such tests are the only realistic basis for judging the validity of pragmatic tests used as standards for specifications.

Because of economic considerations, relatively few full-scale fire tests have been performed to validate the pragmatic tests being used as standards for specifications. Regulatory agencies have to a large extent relied on previous fire experience to select the pragmatic tests needed for their particular situations.

Existing test methods available to regulatory agencies such as the FAA and military departments are inadequate to provide complete guidance for selection of polymeric materials to be used in systems that must face a wide spectrum of aircraft fire scenarios; such test methods are, at best, adequate for screening out individual materials whose fire characteristics are unsatisfactory.

The FAA, military departments, aircraft manufacturers, and aircraft operators have utilized existing test methods to the best of their technical judgements and achieved a reasonable degree of effectiveness. Nevertheless, fire safety of aircraft, like fire safety in all societal systems, requires a major research program to develop suitable knowledge and techniques such as:

Test requirements and needs

Test specifications

Test data

Test extrapolation methods

At the same time there is a need to develop risk-reward equations for societal systems to permit a quantitative measure of obviously necessary trade-offs. This matter and the scenario technique are more fully discussed in the Afterword and Chapter 3.

The committee's conclusions as to the adequacy of test methods generally makes the comments of the following sections appear to single out for blame the FAA, military departments, aircraft manufacturers and operators. Blame is not intended. While the comments are valid when taken against the absolute yardstick of human safety, the organizations noted above have generally performed well in utilizing the technical test methods and data available to them.

6.5.1 Exposure Time to Ignition Source

According to work reported by the National Bureau of Standards in the vertical test, the 60-second flame application time for ceiling and wall panels and the 12-second application time for carpets and draperies and upholstery may be too long to properly predict the fire behavior of certain materials. It should be ascertained whether a better assessment of flame resistance may be obtained with shorter time of flame application. Tests using flame application times of 3, 12 and 60 seconds might permit a better overall assessment of flame resistance.

6.5.2 Test Geometry

The horizontal test, the 45-degree test, and the 60-degree test are generally less severe exposures than the vertical test and, as such, provide opportunities for confusion and for reducing the overall flame resistance of the system by permitting less flame-resistant components.

6.5.3 Type of Ignition Source

ThyC-C-91 Class B candle test and the electrical wire wrapped test are not representative of most types of ignition source.

6.5.4 Allowable Flaming after Exposure

Flame time after removal of the flame should be limited so as to provide a minimum opportunity for ignition of adjacent materials within the capabilities of available materials. Flaming drippings clearly represent opportunities for flame spread and should be minimized.

6.5.5 Test Conditions

Flame spread rates, ignition times, and time of drippings are determined on

single specimens in the absence of any other heat flux to the specimen; consequently they may not represent the response of the material in an actual fire environment.

6.5.6 Oxygen Index

The oxygen index test, whether at ambient or elevated temperature, does not offer promise as an alternative test because it employs downward burning which does not necessarily simulate actual fire conditions and because it lacks correlation with representative fire situations.

6.5.7 Heat Release

Heat release may be defined as the heat produced by the combustion of a given weight or volume of material. This characteristic is relevant to fire safety in that a material that burns with the evolution of little heat per unit quantity burned will contribute appreciably less to a fire than a material that generates large amounts of heat per unit quantity burned. Some measures of heat release are heat of combustion, heat release rate, and heat evolution factor.

Federal Aviation Regulations at the present time do not provide for any standards or specifications on heat release, possibly on the basis that materials that do not ignite will not burn. Fire experience, however, indicates that materials that meet laboratory specifications can ignite and burn in full-scale scenarios. The heat release and other characteristics of aircraft interior materials therefore should be considered in evaluating overall fire safety, and appropriate test methods need to be developed.

6.5.8 Smoke Evolution

Smoke density may be defined as the degree of light or sight obscuration produced by smoke from burning or pyrolyzing material under given conditions of exposure. This characteristics is relevant to fire safety in that an occupant has a better chance of escaping from an aircraft cabin if he can see the exit and is not incapacitated by smoke constituents. Some measures of smoke density are degree of light absorption and specific optical density.

Current Federal Aviation Regulations contain no standards or specifications on smoke evolution,* and smoke density standards should be established to make egress requirements realistic. Because requirements for egress capabilities call for an evacuation time of 90 seconds, smoke density standards should be set as low as possible within the capabilities of available material – i.e., for a period perhaps as long as 180 seconds or longer to provide for stragglers. (See Section 6.5.9 for toxicity considerations). The NBS smoke density test is the most useful smoke test presently available.

*Such standards are now contemplated by the FAA.

6.5.9 Toxicity

The NBS smoke density chambe , modified to determine and correlate combustion gas composition, and pyrolytic products with animal exposure, is one promising test method under development; it is widely used by many laboratories. Improvements are under study at the University of Utah and elsewhere.

The toxicity test method developed in Japan (JIS 1321) is another possible approach because it combines gas analysis and animal response at similar combustion energy levels. The toxicity test developed in Germany (DIN 5274) is less promising because it is less representative of fire conditions, the specimen size is limited, and the animal expsure time is too long.

Toxicity guidelines must be developed before interior material toxicity requirements can be specified. A more extensive discussion is presented in Chapter 7 of this report and Volume 3 of the series.

6.5.10 Fire Endurance

Fire endurance may be defined as the resistance offered by a material to the passage of fire. This characteristic is relevant to fire safety in that a material (considering its related installation, detail, and structure), that will contain a fire, provides more protection than one that will fail to contain the same fire, all other factors being the same in both cases. Some measures of fire endurance are penetration time and resistance time.

Current Federal Aviation Regulations require that each receptacle for towels, paper, or waste must be at least fire retardant and provide means for containing possible fires. Requirements for protection against fire breaking out of a lavatory unit or other compartment of a fuselage must be evaluated on the basis of a credible scenario.

6.5.11 Combustible Gas Evolution

Combustible gas evolution may be defined as the amount of combustible gases evolved from the burning or pyrolysis of material, and their tendency to produce flashover, under given conditions of exposure. There are no adequate tests to completely define combustible gas evolution. Studies at the National Bureau of Standards have been commissioned by FAA to define the flash fire propensity of polymeric materials and develop appropriate tests to assess the phenomenon.

6.5.12 Ease of Suppression

Ease of suppression may be defined as the relative facility with which the burning material can be extinguished with a particular extinguishing agent. This characteristic is relevant to fire safety in that a material that is easily extinguished by a hand extinguisher or automatic extinguishing system presents less hazard than one that defies extinguishment. FAR 25.851 requires hand fire extinguishers containing agents "appropriate" for cabin fires, perhaps the term "appropriate" should be defined in a standard.

6.5.13 Prediction of Actual Fire Behavior

No available test method provides a prediction of actual fire behavior. The fire scenarios described in Chapter 3 demonstrate that current FAA regulations would not prevent such scenarios from occurring. Review of the data reported by the AIA in 1968 in the light of recent fire experience and toxicity criteria indicates that the change in cabin materials from those in service in 1967 to current materials did not prevent such fires.

6.5.14 Discussion of Testing Adequacy for Total Systems

It is questionable whether the self-extinguishing interior materials now permitted by the Federal Aviation Regulations and their specified test conditions represent the minimum acceptable fire safety level for aircraft certification. While these requirements tend to lower the rate of fire spread and temperature rise in an aircraft cabin fire, and thus, extend the time available for escape, the fire hazard scenarios described in Chapter 3 indicate that the present level may be inadequate to prevent some important types of scenarios from occurring. Research, therefore, is needed to correlate test methods with the fire hazard of polymeric interior cabin materials, air ducts, an; panelings in actual cabin fire conditions.

6.4.15 Modeling and Scaling

Modeling and scaling techniques are not adequately developed at the present time to justify reliance on these techniques for fire hazard tests for aircraft interior assemblies (a discussion of this subject is presented in the Afterword).

6.6 Programs Needed for Improved Standards

Recent work at NASA Ames Research Center and other laboratories has indicated that large-scale simulation of aircraft interior fires is needed to accurately evaluate the criteria for judging relative fire safety of various materials and systems. Research work should be performed to correlate the mass availability, area exposure, materials configuration, ignition severity factors, and other parameters (e.g., toxic gas evolution, smoke obscuration, and flame spread) with the behavior of materials in aircraft interiors under real fire conditions.

To provide the data base for developing improved fire safety standards for aircraft, four types of test must be performed:

1. Full-scale fire tests involving sections of wide-body and standard-body jet fuselages and employing both internal ignition sources and external fuel-fed pool fires.

2. Large-scale mockup tests, such as 8-foot corner or compartment test configurations and 747 lavatory modules.

3. Laboratory-scale tests, including the FAA vertical burn tests, ASTM E-162 radiant panel test, Ohio State University release rate apparatus, NBS smoke density test, NASA Ames T-3 test, etc.

4. Basic property tests covering oxygen index, heat of combustion, ignition temperature, etc.

To the maximum extent possible and to achieve earliest results, these tests should employ direct animal response and analytical methods to measure toxic gas evolution. The various parameters recorded through the smaller-scale tests should be compared and correlated with the relevant parameters in full-scale tests to determine the relative ability of the smaller-scale tests to predict behavior under actual fire conditions.

The toxic gas threat has been identified as a major factor in some fire scenarios. Tests for the toxicity of combustion and pyrolysis products of aircraft interior materials should be rapidly developed to permit promulgation of toxicity standards.

As noted above, given the present state of knowledge, it appears that such tests should employ direct animal response. To supplement animal response studies, acceptable analytical methods and toxicity criteria should be established for the toxic gases known to be generated by aircraft interior materials under combustion or pyrolysis conditions. Such gases may include, but are not limited to:

1.	Acrolein	11.	Styrene
2.	Acetaldehyde	12.	Acetone
3.	Antimony bromide	13.	Benzonitrile
4.	Antimony chloride	14.	Methyl cyanobenzene
5.	Carbon monoxide	15.	Hydrogen bromide
6.	Carbon dioxide	16.	Hydrogen chloride
7.	Nitrogen oxides	17.	Hydrogen fluoride
8.	Hydrogen cyanide	18.	Vinyl fluoride
9.	Benzene	19.	Allyl fluoride
10.	Toluene	20.	Carbonyl fluoride

After toxicity hazards have been adequately defined and tests prescribed, the toxicity hazards of aircraft interior materials should be determined by competent laboratories utilizing standard test procedures; the selection of test conditions can be decisive in determining the toxicity of gases evolved.

6.7 Conclusions and Recommendations

Conclusion: "Self-extinguishing" cabin and cargo compartment interior materials now provided by the Federal Aviation Regulations and their specific test conditions do not represent the minimum acceptable fire safety level for aircraft certification based on today's knowledge. *Recommendation:* Research is needed to correlate test methods with the fire hazard of polymeric interior cabin materials. Additional large-scale testing is required to provide the data base for validating small scale tests. Modified regulations should be promulgated if required.

Conclusion: Current material flammability standards are based solely on "flame resistant' criteria which do not adequately represent the most severe fire hazard configuration or subject the material to real fire conditions. *Recommendation:* ASTM E-162, the radiant panel test, should be employed to determine the

"flame resistance" of cabin and cargo compartment interior materials, since it more closely represents real fire conditions than do currently employed tests. For all cabin and cargo compartment interior fabric materials, the vertical test should be employed. Further, three separate tests, using flame application times of 3, 12, and 60 seconds, should be employed in the vertical test. Acceptable performance levels in both the E-162 and vertical test should be based on the responses of these materials in large-scale tests.

Conclusion: Current flame-resistant and self-extinguishing criteria neglect other important flammability characteristics of polymeric materials, especially smoke and toxic gas production. *Recommendation:* The NBS smoke density test (NFPA 258) is the most useful smoke test presently available and should be employed in a smoke standard for interior cabin materials. The variation of smoke production with heat flux should be evaluated. The FAA should establish standards governing the smoke and toxic gas emission characteristics of compartment interior materials when subjected to real fire conditions. Further research and study are necessary before this recommendation can be implemented.

Conclusion: Polymeric fuel additives show great potential to reduce the fire hazard to aircraft polymers. This refers to the hazard arising from fire fed by fuel spillage following a survivable crash. *Recommendation:* Development of modified fuels should be continued. A test method should be developed for screening modified fuel candidates under conditions that correlate with the most severe fuel release and polymer ignition conditions expected in a survivable crash.

6.8 References

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CHAPTER 7

SMOKE AND TOXICITY

7.1 Introduction

Major factors that influence survival of persons subjected to fire environment in confined spaces are:

1. Heat destruction of tissues due to thermal shock.
2. Toxicity from oxygen deficiency, exposure to carbon monoxide and other noxious gases, aerosols, and particulate material.
3. Presence of smoke with consequence reduction of vision and visibility.
4. Fear or outright panic resulting in secondary mechanical trauma.

All of these factors may be involved in a fire depending on the fire scenario and the individuals in the confined space. The nature, shape, and quantity of materials undergoing combustion or pyrolysis determine the number of factors involved in any fire and therefore the degree of hazard to human survival.

Modern aircraft are examples of a confined space in which fire represents a serious hazard. The material that undergoes combustion or pyrolysis (excluding, for the purpose of this report, engine fuel, lubricants, and hydraulic fluids) consists of natural and synthetic polymers. In general, with the exception of wool, cotton, paper, and other cellulosic materials, the large majority of flammable materials on aircraft are synthetic polymeric materials.

As shown in Chapter 5, materials currently in use cover a broad spectrum. The choice of polymeric materials permits the modern wide-bodied jet airliner to incorporate materials that meet or exceed current FAA fire safety requirements. The FAA-flame-resistance requirements (FAR 25.853) involve burn tests that are commonly referred to as the 60-second vertical, 15-second flamout, and 3-second drip test. Currently, the FAA has no specific requirements concerning smoke production or noxious gas generation under fire conditions, but there is evidence of prospective early action by the FAA in this area.

7.2 Perspective on Experimental Data

The past decade has seen an increasing number of studies concerned with noxious gases and smoke resulting from thermal degradation of polymeric materials. Although the general implications of these studies will be examined in Volume 3 of the committee's reports, particular points pertinent to aircraft fires are discussed here. (The reader also is directed to Appendix M for a review of the current state of knowledge.)

Pyrolysis or combustion products of the polymers used in aircraft construction have been found to include carbon monoxide (CO), carbon dioxide (CO_2),

hydrogen cyanide (HCN), oxides of nitrogen (NO_x), ammonia (NH_3), hydrogen sulfide (H_2S), phosgene ($COCl_2$), and many other compounds. The physiological hazards of these gases are described in Appendix I and Kimmerle provides a more detailed complication of effects at various atmospheric concentrations.

From fires in confined spaces, the predominant toxic thermal degradation product is CO. Incapacitating or lethal amounts of CO can develop within minutes (Appendix H presents a brief review of CO toxicity).

The net physiological response from CO and other thermal degradation gases is far from clear, although awareness of this problem is increasing.

Fire situations can have an extremely complex toxicology. If a lethal CO atmosphere is not reached, other lethal or disabling factors may still be present. For example, in the series of experiments reported by Cornish and Abar pulmonary injury from HC1 developed in the absence of lethal effects from CO. A more subtle effect is noted by Effenberger. In his series of experiments, burning polystyrene did not cause rats to die or develop significant amounts of carboxyhemoglobin, but the polymer yielded "styrene" which apparently has an immobilizing effect on the rat. If this interpretation may be extended to fires involving humans, death could result because ability to escape from the fire is impaired. In these animal experiments, the determination of immobilizing effect was based on performance in the swimming test, a simple exercise method also favored by Kimmerle to provide comparative data. However, animal exercise tests involving such unusual stress as carrying weights may be difficult to relate to fire situations.

Smoke presents a number of hazards and an infinite variety of compositions. Smoke is basically a mixture of unburned carbon particles and inert materials evolved from combustion but may contain irritants absorbed on the particles and be mixed with thermal decomposition gases. The hazards of smoke may be both physical (blocking vision) and physiological (local or systematic chemical irritation and toxicity, heat injury, and panic). (Appendix I surveys the hazards from smoke and describes current measurement techniques.)

7.3 Experimental Data Based on Aircraft

In 1969, Gross, Loftus, Lee, and Grey reported their measurements of smoke produced during flaming and smoldering exposures on 141 aircraft interior materials, including sheet and laminate materials, fabrics, rugs, pads, insulation, and films. The materials were mostly synthetic and included polyvinyl chloride, acrylonitrile-butadiene-styrene, polymethyl methacrylate, wool, cotton, modacrylics, polyamide (nylon and aromatic types, polypropylene, urethane foam, chloroprene glass fiber, and paper. Smoke was measured by the progressive attenuation of a light beam passed through the smoke aerosol within an enclosed smoke chamber. Most of the materials produced more smoke during flaming exposure but certain materials produced significantly more smoke under smoldering conditions. Materials such as nylon, polysulfone, and polyethylene melted at comparatively low temperatures and produced less smoke. All urethane foams produced more smoke under smolder-

ing conditions, except in one case where the material shrank and received less radiation. Chloroprene, ABS, methacrylate, and PVC materials nearly always produced more smoke under flaming conditions. Varying amounts of CO, HC1, HCN, HF, and SO_2 also were detected (see Appendix J). This study illustrates the very wide range in smoke density values and specific toxic gases from materials used in a common location such as aircraft interiors.

The FAA project to study the burning characteristics of airplane interior materials, reported by Marcy in 1970, involved 28 tests and used an intermediate-size model to permit economical variation of a single parameter. A 640-cubic-foot trailer served as a cabin mockup enclosure. Some of the more significant results were:

1. Seat materials with a low flammability rating burned only in the area of direct flame contact, but the more flammable materials continued to burn at an accelerated rate until a flash fire (rapid burning of accumulated hot combustible gases) developed. Fire retardant neoprene foam was superior in that it did not flash when heated by an incandescent heat source.

2. Ventilation caused a much more drastic fire with dense smoke and large CO concentrations due to the rapid combustion of foams.

3. A high rate discharge of bromotrifluormethane was effective in bringing the fires under rapid control to maintain a survivable environment.

A 1974 NASA report describes a series of three full-scale aircraft cabin flammability tests conducted in a 15-foot-long section of a Boeing 737 fueselage furnished to simulate the passenger cabin of a commercial jet transport. Test 1 was designed to provide a baseline for the series using the guidelines of earlier tests conducted by the AIA. The materials tested were in use before the 1968 Federal Air Regulations on the flammability of aircraft cabin materials and included pre-1968 Boeing 737, 727 and 707 material configurations. Smoke visible immediately after ignition of the JP-4 fuel prevented visual observation of the fire after some 60 seconds. Major damage with areas of complete destruction resulted from a flash fire that began in approximately 95 seconds and caused a rapid increase in cabin temperature followed by oxygen depletion to a concentration of less than 5 percent.

Materials in Tests 2 and 3 were newer fire-resistant materials representative of interior materials installed in NASA Gulfstream aircraft. Test 2 also yielded immediate smoke from the JP-4 ignition fuel and the seat cushion above the fuel fire. Visibility was lost at approximately 150 seconds; however, the fire behavior was rated at typical open fire without a rapid-burning flash fire. Cabin temperature increased, peaked at approximately 150 seconds, and then decreased as atmospheric oxygen gradually approached the 15 percent level. Damage was confined to the seat above the fire and the adjacent side wall and ceiling; it was "far less" than in Test 1. Test 3 was similar to Test 2, but was conducted with smokeless fuel (acetone and methanol) that required more time to ignite. Smoke production was slight until 80 seconds into the test and then increased slowly. As in Test 2 a "typical open fire"

developed but major damage was sustained only by the seat directly above the fuel fire. Both Tests 2 and 3 showed that use of the improved materials would provide some degree of additional safety during aircraft cabin fires. Substantial ignition sources would be required to ignite the improved materials. When ignition from such sources occurs, the fire would remain somewhat subdued for a significant time, thus permitting adequate time for implementation of extinguishment procedures.

Two recent preliminary studies may be mentioned. In experiments with mice on two "space-age" fire resistant materials, a chlorinated aromatic polyamide and a copolymer of vinylidene fluoride and hexafluoropropene, the resulting CO levels were not considered lethal or incapacitating, suggesting that other gases may have contributed to death. A joint project by the FAA and NBS showed that a flash fire cell using a high voltage arc produced a flash fire within 2 minutes in latex foam and polyethylene foam, compared to flashover time of 3 to 4 minutes for polyethylene and acrylic resin and no flashover for PVC and cellulose.

7.4 Clinical Data Based on Aircraft Fires

Quantitative toxicological data based on aircraft fire victims are limited; however, Smith and associates have described the results of their forensic investigations as follows:

Two commercial aircraft accidents in the United States during the 1960's (Denver, Colorado, 1961; Salt Lake City, Utah, 1965) contributed greatly to the initiation of the present concern over the toxic hazard of the gases generated in aircraft fires. These accidents were of special significance because careful analysis indicated that few, if any, of the occupants would have suffered significant physical injury from the relatively mild impacts involved; yet a total of 60 persons perished as a result of thermal and chemical injuries sustained in the ensuing fires.

Carboxyhemoglobin measurements on 16 victims of the Denver crash revealed CO saturations ranging from 30 to 85 with a mean of 63.3 percent. Similar analyses on 36 victims of the Salt Lake City accident yielded CO saturations ranging from 13 to 82 percent, the mean being 36.9. The lower carboxyhemoglobin values found in the second accident have been attributed to the fact .hat fire was present within the aircraft before evacuation could be attempted and that the survival time of many victims must have been shortened by direct thermal effects. It has also been assumed that gases other than carbon monoxide must have contributed to the toxicity of the cabin environment, but there is no suppoiting evidence for the assumption.

In 1970, blood samples from victims of an aircraft crash followed by fire (Anchorage, Alaska, November 1970) were analyzed for the presence of cyanide; the first time, to the best of our knowledge, that such analyses had been made on victims of an aircraft fire. Measurable amounts of cyanide were found in 18 of the 19 specimens submitted, accompanying carbon monoxide saturations ranging from 17 to 70 percent. In the one sample in which cyanide could not be detected, the carboxyhemoglobin concentration, 4.9 percent, did not exceed that which could

result from smoking, indicating the probability of death on impact. Blood cyanide levels in these victims corresponded closely with those reported in the literature for victims of structural and vehicular fires ranging from the lower detection limit (circa 0.01 μg/ml) up to 2.26 μg/ml. The relationship between cyanide levels and carboxyhem oglobin content varied in random fashion, perhaps representing relative proximity of the victims to cyanide-producing materials. Alternatively the varying cyanide levels reported may be due to uncontrolled autoproduction of cyanide in and from the tissues.

Nothing in these findings permitted speculation concerning the relative contribution of the two gases to lethality. In addition, there was no way of assessing the possible contribution of other gases that must have been present in the pyrolysis mixture to which these victims were exposed.

7.5 Clinical Aspects of Various Fire Scenarios

As discussed in Chapter 3, the fire scenarios of most concern in aircraft are the ramp fire, the in-flight fire, and the post-crash fire. In all cases, the hazard to human survival depends on the concentration and time involved in exposure of humans to the actual flames or products generated by pyrolysis or combustion of the material being consumed. The order of hazard is:

1. *Least in the ramp or ground fire* when *smoldering* conditions occur and exit from the aircraft is available. In the absence of respiratory support, the hazard to life then depends on intensity of smoke and irritants that may obscure vision and interfere with respiration. In such cases, panic may lead to disorganized egress and consequent trauma. The toxicity of the products involved depends on the chemical and physical composition of the materials undergoing pyrolysis or combustion and the prevailing fire conditions.

2. *Intermediate in the in-flight fire* when the fire is in the smoldering state and evident to the passengers, crew, or cabin attendants because of smoke and/or irritant gases ithe atmosphere. Since mass exit from the airplane is impossible under in-flight conditions, the degree of hazard is directly related to the nature anu quantity of the atmospheric contaminants (toxic gases and smoke). Under the assumption that a respiratory life support system containing oxygen free of contaminants is available, the hazard is primarily related to the efficiency of the life support system and the capability of controlling the fire. The utility of the present life support system and adequacy of extinguishment facilities should be reviewed.

3. *Greatest in the post-crash fire* when there is a rapid onset within 90 seconds or less of uncontrollable flames that engulf the victim and result in the thermal destruction of the respiratory tract and/or the body generally (see Section 3.2.3). Since survival depends on escape in seconds, sufficiently rapid evacuation is often impossible, especially in large airplanes with several hundred passengers. The only way to effectively reduce the life hazard in such cases is: (a) prevent

exposure (preferably by eliminating the release of fuel that provides the flame source); (b) provide multiple emergency exits for instantaneous exit; and (c) provide a structure that will withstand or minimize fuselage rupture or separation and will insulate the interior and endure the post-crash fire long enough for external extinguishment or burnout.

7.6 Evaluating the Hazards of Toxic Fumes and Smoke

7.6.1 Comparison of Materials

Valid comparisons of different materials must be based on similar or reasonably standard conditions. The desirability for a standardized test procedure pertinent to proposed use application is obvious. However, real fires possess two essentially uncontrollable variables – oxygen supply and temperature – that make selection of such test procedure inherently difficult. Generally, laboratory thermal degradation tests in an oxygen-lean atmosphere are described as pyrolysis tests while combustion with actual flame indicates an oxygen-rich atmosphere. Since either pyrolysis or combustion can be the more hazardous depending on the nature of the material being consumed, a standard procedure should take both categories into account, either separately or together.

7.6.2 Thermal Decomposition Temperatures

Fire temperature depends on the pyrolysis and/or combustion processes and also the caloric value of the product or products comsumed by fire. For the thermal decomposition of wood, several analysts have followed a classification of four distinct temperature zones (see Appendix K). However, the committee is unaware of any attempt at such a classification for the multitude of synthetic polymers that exist today.

7.6.3 Method of Study

Recent literature describes the four types of methods discussed below (see Appendix L).

7.6.3.1 Analysis

Testing to identify the chemical components involved can help in understanding the effect of altering variables such as temperature and oxygen. The relative hazard or lethality of the product can be estimated with reasonable confidence if a single component, such as CO or HC1, is clearly predominant and no other significant source of stress is present. If thermal degradation generates a significant quantity of miscellaneous gases, heat, and/or smoke, the net physiological response is difficult to estimate; however, analysis of such mixtures or their degradation products is becoming less difficult with the development of new more sophisticated (and expensive) analytical tools. To compound problems, finished products may be composed of basic elements, antioxidants, filler, additives, and finishes, and even major percentage compositions often are not stated.

7.6.3.2 Biological Testing

Data obtained from tests on laboratory animals can be expressed as the LC_{50} or concentration expected to produce death in 50 percent of the exposed animals and the EC_{50} or concentration expected to produce a specified effect such as incapacitation, in 50 percent of the exposed animals. It is in this latter area of biological tests for toxicity that special attention is required. A safer product from the standpoint of a flammability test does not always result in a more desirable product in that:

1. Structure modification or additives may result not only in retarded combustion of the polymer but also in increased toxicity of decomposition gases and/or dense smoke from the smoldering of the polymer when it is exposed to external heat.

2. Many of the more common fire retardants contain halogens, such as chlorine and bromine, that theoretically make possible the production of thermal decomposition products such as hydrogen chloride (HC1), phosgene ($COC1_2$), and hydrogen bromide (HBr).

3. The presence of nitrogen atoms, either in the polymer or in the additives, introduces the possibility of thermal degradation to HCN or NO_x.

4. Polymers based on propoxylated trimethylopropane polyols and fire-retarded with phosphorus-coating retardants may yield highly toxic bicyclic phosphorous esters when thermally degraded.*

7.6.3.3 Extensions of Analysis and Biological Testing

Present models include combined testing, predictive testing, and "room" or large-scale fire tests.

7.6.3.4 Epidemiological Studies

Critical analysis of this kind has been applied to fire toxicity only recently and has generally been defined according to a particular land area. For air transportation, there is a need for evaluated reports from commercial aircraft fires that provide comprehensive casualty data, including quantitative toxicological and pathological evaluation of victims. Only recently have such casualty data started to become available. To consider only one decomposition product, a recent discussion of HCN as a major lethal factor in aircraft fires indicates not only the current interest and concern in this area but also the difficulties that may be associated with such analysis.

7.6.4 Evaluation for Aircraft Use

Obviously, products or formulations require more stringent evaluation when intended for aircraft use than for many other applications. The unavoidable pres-

*Unpublished letter from I.N. Einhorn, *et al.*, to L. J. Sherman, Consumer Product Safety Commission, August 26, 1974.

ence of large quantities of highly flammable fuel and the limited exit facilities inherently expose aircraft occupants to a greater fire and toxicity hazard than exists in more ordinary occupancies. If any new products or formulations are used in aircraft in appreciable quantity, their potential toxicity when burned must be evaluated along experimental guidelines and reviewed in the context of available epidemiological data.

7.7 Conclusions and Recommendations

Conclusion: At the present time it is difficult to establish the degree to which combustion and thermal decomposition products from synthetic polymers on board aircraft are involved in hazard to human survival during aircraft fires. *Recommendation:* A research program should be established in two or more qualified institutions to develop criteria and practices for determining the degree to which polymers contribute to human morbidity and mortality in aircraft fires.

Conclusion: Although carbon monoxide is a major toxic hazard in polymer fires, current data indicate that, under both clinical and experimental conditions, thermal decomposition products other than CO may be involved in the hazard to human survival if certain types of polymer systems and/or fire-retarded polymers undergo combustion or pyrolysis. Either pyrolysis or combustion can be the more hazardous depending on the nature of the material being consumed. Also, the investigation of the overall biological effect of polymer combustion products including synergism has been inadequate in that autolytic and hydraulic (as opposed to pyrolytic) phenomena have been ignored, *inter alia*. *Recommendation:* A hazard assessment procedure that will take both pyrolysis and combustion into account should be developed. Polymers that will serve structural, economic, and design requirements, and offer the least life hazard in fire situations, should be utilized. It also should be noted that the contribution to life hazard generally will depend on both the total amount and particular application of the polymeric material.

Conclusion: Deaths have occurred from toxic gases in both in-flight and other aircraft fires in accidents that otherwise might have been survivable. Additionally, laboratory evidence indicates that smoke can be an important factor in escape and survival due to obscuration of exits, lachrymation, and panic and toxicity. *Recommendation:* The efficient and safe utilization as well as the toxicology of fire-suppressant chemicals (e.g., halons) should be investigated more fully. Since, in fire situations, toxic thermal decomposition products react directly on the respiratory system or are absorbed through it, the utility of the present life-support system also should be assessed and the feasibility of developing life support systems independent of the cabin atmosphere for use aboard aircraft should be examined.

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AFTERWORD

SOCIETAL CONSIDERATIONS RELATED TO FIRE SAFETY ASPECTS OF POLYMERIC MATERIALS IN AIRCRAFT

The environment in which society exists today reflects complex sociotechnical systems and is one of relatively high risk to the individual. The risk has developed gradually through small accretions without full assessment of alternatives and without the informed consent of individuals who will be affected. Thus, individuals usually are faced with a *fait accompli** and can depend only upon the scientific/technical community and the government to assess and regulate risk by analyzing the consequences of actions in terms of risk and the options for risk reduction. It must be recognized, however, that regulation established to effect "absolute safety" is chimerical (it is clear that such an environment cannot exist).

In this context and in the light of its basic biases toward human survival, the committee has prepared this "Afterword" to address the societal consequence of materials use when fire is a design consideration. While it apologizes for less-than-perfect expertise, the committee believes it inherent in its overall responsibility to draw attention to the following five problem areas related to the use of polymeric materials but not treated in detail in the narrow scope report:

1. Direction and coordination of efforts
2. Financial considerations
3. Methodology
4. Communication
5. Regulation

Direction and Coordination of Efforts

In the United States, there is no overall direction guiding efforts related to the fire safety aspects of polymeric materials. Basic data come from a large number of government, university, and commercial laboratories, and evidence on use comes from codes, administrative regulations, and the laws of Congress as well as other government bodies.

The committee does not wish to imply that work has not been done on this subject since government agencies (e.g., the Departments of Defense, Commerce,

*Consider, e.g., the increased flammability of the environment in general resulting from such substitutions as plastic furniture for wood furniture, polyurethane foam for glass fiber insulation, polyurethane foam for hair and wool matresses and acrylic and nylon carpeting for wool carpeting. In many cases, the application of new technology has increased the probability of ignition, burning, fire propagation, and evolution of toxic gases, and the United States now is reputed to experience the highest per capita fire loss (property, productivity, life and injury) of all industrialized nations (see author, *America Burning,* The Report of the National Commission on Fire Prevention and Control, Richard E. Bland, Chairman, May 4, 1973, page 7.)

Transportation, Interior, Housing and Urban Development and the National Aeronatuics and Space Administration and Consumer Product Safety Comm ission) have mounted various programs to improve safety in specific systems (aircraft, rapid transit, coal mines, housing, etc.). In addition, commercial organizations have conducted in-house programs to improve product safety and fire departments have collaborated with other institutions (e.g., New York City Fire Department and Polytechnic Institute of New York) to increase fire safety. Nevertheless, except in some cases, these efforts have not been effectively coordinated. The aircraft industry (transport and military) has not been free of this criticism although the coordination in this area has been far better than in others (e.g., materials for consumer products or housing).

The committee believes that the evidence available to it dictates that it draw attention to the following factors:

1. Fire safety aspects of polymeric materials is a problem deserving of national attention. This situation is no less true of polymers used in aircraft (addressed by the committee in this report) than in other important fields that will be addressed in other reports).

2. To minimize duplication of effort and maximize utilization of available resources, a federally supported program is necessary to identify, catalog, and report continuously on new, ongoing, and completed research work related to the fire safety aspects of polymeric materials. (Plastec* may be used as an example of the sort of effort the committee believes warranted).

3. A single data center (like the U.K. Home Office Fire Center in the Building Fire Research Station) should be established to record and coordinate fire data of all kinds including aircraft fire data. For this purpose it may be desirable to institute standardized reporting forms.

The committee wishes to bring this need for coordination and direction of fire safety efforts to the attention of the National Academy of Sciences Committee on Science and Public Policy as it makes recommendations concerning the development of public policy and the planning and management of "federal research and development" in line with its charge (NAS-NRC-NAE News Report, February 1974). In the area of aircraft fire safety, the committee believes such coordination and direction to be essential.

Financial Considerations

Current financial support of research and development relating to fire safety of polymeric materials for use in aircraft comes from a variety of sources (e.g., NASA, DoD, FAA, NFPCA, NSF, etc.). Such support is usually tied to a limited objective relating to a specific deficiency or task to the supporting agency. Federal

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*Plastec is the acronym for Plastics Technical Evaluation Center, Picatinny Arsenal, Dover, New Jersey, 07801, an agency of the Department of Defense, ODDRE.

government funding is largely on an annual basis. The effect of this situation can be illustrated by a number of specific cases:

1. The unsatisfactory nature of the existing fire tests for system interaction has been well-known to experts in the aircraft field for some time; nontheless, no avenue is available to rectify the deficiency. Similar constraints have prevented consideration of the question of economic restraints vs utilization of "better" materials, the problem of materials evaluation on a "problem solving" level as compared to a "beating the test" or "meeting the standard" level, and the problem of communication between industry and the federal agencies.

2. The adverse aspects of potential toxic side effects from "fire retardation" treatments has become better known, but no mechanism is available through which to maximize the use of the knowledge.

3. New developments that promise substantial improvement in degree of public transport safety are not brought to early fruition; the reason frequently cited is that the economic burden on a commercial source may be such as to discourage that source.

If reasonable progress is to be made, the committee believes that studies of system use of polymeric materials require substantial additional funding and continuation of support at the existing relatively low level will provide only marginal results. While the method of fund raising is beyond the scope, and, indeed, the expertise of the committee, it believes that it can, comprised as it is of technical people, make a judgement as to source of funds relative to the anticipated benefits from projects and it is this matter which is addressed below.

By definition, projects related to the fire safety aspects of polymeric materials are directed toward public benefit irrespective of local geography. Since the general welfare is concerned, these projects are a proper area for federal support. However, as a matter of justice, public funds should not be spent to confer proprietary benefits on any individual or group of individuals and hence, materials should not be evaluated at the public expense without full characterization. Since the travelling public as a whole will benefit from the studies recommended in this report, it seems logical that the major portion of the funds required should be supplied by the Federal Government.

It is a matter of concern that funds allocated to fundamental academic research (NSF-RANN) have been halved and may be phased out. There is no substitute, in the long run, for expansion of the data base by publication of academic basic research.

The major aircraft manufacturing companies are expending sums of money that are sizable compared to the amounts of materials used in their products. They appear to cooperate fully with government agencies and laboratories in information interchange and joint project participation. Their efforts as well as those of their polymeric material suppliers often result more or less accidentally, in the same materials being developed for and used in competing aircraft. They express a continuing demonstrated interest in public safety. For competitive and anti-trust rea-

sons, however, information interchange between the companies is substantially hampered and mistakes made and lessons learned cannot always be shared.

Thus, a need exists to develop a mechanism through which competitive information relating to fire safety in publicly used aircraft can be shared.

When faced with similar but much larger problems in connection with quality assurance of vendor supplied components, aerospace companies developed the CASE (Coordinated Aero Space Supplier Evaluation) concept for information interchange, primarily for defense oriented contracts, Aircraft manufacturers support CASE with their funds. A similar approach, possibly a new element of CASE, supported by the FAA, might provide a suitable approach to this problem.

Aircraft operators supply a substantial portion of the interior furnishings of a commercial aircraft. These are purchased in accordance with FAA requirements as stated in the regulations. These requirements generally relate to properties of individual materials or components that were tested under laboratory conditions. No system analysis review is required by the FAA since the fire safety technology does not support such a review. Few or no expenditures are made directly by the operators in support of total system fire safety, partially due to the fact that there is presently no way for them to present a superior system if one or more components do not meet specific federal requirements. No incentive exists for aircraft operators to develop improved systems and without incentive (or duress) operators of transport aircraft are not likely to adequately fund their often-expressed desires for improved systems.

It may be significant to note that the technical community available to support research in fire safety aspects of polymeric materials is small. An order of magnitude increase in research and development funds could not be effectively utilized. The committee concudes that an orderly compound annual increase of expenditure of about one-third of the 1974 expenditure would be appropriate for the duration of the national needs ithis area. The emphasis should be directed toward both civil and military needs.

In summary, the committee has concluded that current financing is inadequate to support the national need; present projected reductions in RANN activity will make matters worse; and a substantial increase in effort should be supplied by the Department of Defense, NASA, and the FAA. Specifically, the committee believes that substantially more could be done with the national resources allocated to fire safety studies if:

1. An overall review of the full matrix of requirements and deficiencies were conducted to serve as the basis for allocation of research and development resources to government laboratories, universities, and other laboratories. (While recognizing that some overlap may be desirable, unnecessary duplication of programs could be eliminated and priorities assigned using a recognized objective system).

2. A national program incorporating regular review and revision were instituted and given long-term support of a substantial nature (such an approach should

mitigate the serious problem created by the fluctuating nature of current funding that prompts many of most gifted investigators to abandon the field).

3. Conflicting or partial data advanced by competing activities were resolved.

4. In the interests of more effective utilization of funds now expended by aircraft manufacturers, the FAA should actively explore utilization of a CASE-type approach.

The committee also believes that additional support for the following priority-ranked activities is needed:

1. Materials development.

2. Full-scale testing of typical aircraft configurations for flammability, toxicity survival, and egress, including development of small-scale tests, based on knowledge derived from full-scale tests.

3. Development of a methodology for system fire performance analysis, including parameters and equations for risk assessment and trade-off.

4. Development of improved procedures of modeling techniques.

5. Development of computer modeling techniques, in order that, when operated in conjunction with the full scale tests, small scale tests will bring positive results at lower costs.

6. Evaluation of the contribution to fire hazard of the air transport fire load selected and supplied by the airlines. This fire load can and does in fact vary widely with respect to potential flammability and hazard even though all the materials used do comply with FAA regulations. This is related in part to the inadequacy of the current state of knowledge, of the test methods on which FAA regulations are based, and in part to the varying degrees of economic pressure felt at the time the selection is made.

Methodology

Complex systems cutting across many segments of society and national boundaries can seldom be adequately described in semantic terms. It becomes necessary to invent a precise series of definitions based on universally accepted standards (i.e., mathematical definitions). Invention and acceptance of a mathematical description process has preceded most fundamental advances in technology, certainly in the chemical, physical, and nuclear fields. Wherever there is immense complexity (and large potential reward), such development is required. This is the case here.

The composition of most polymers, can be chemically defined. At some time in the future it should be possible to predict the fire performance from the chemical composition and physical characteristics if a number of developments in this area now being undertaken succeed. At the other end of the spectrum is a computer-based retrieval system to identify materials from measurements of their decomposition products, recording them and comparing them to information in the retrieval library (such as that method utilized at the Flammability Center of the University of Utah*).

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*Einhorn, I. N., *et al.*, *The Physiological and Toxicological Aspects of Smoke Produced During Combustion of Polymeric Materials,* Proceedings NSF/RANN 61-3360 Conference on Fire Research, May 28–29, 1974.

There is, however, no effort underway to bring these and other laudable attempts into a cooperative cohesive matrix or to ensure that the data can be communicated effectively. The synergistic effects needed to make rapid progress are unlikely to develop. Such a mathematical approach would make possible the development of other elements of the needed methodology.

Systematic testing on a larger scale is required because there is no effective substitute at this time. Full-scale testing, however, is expensive and must be carefully designed to obtain maximum results. Reflecting the lack of central direction in fire research efforts, full-scale tests conducted to date usually have had limited objectives, used limited measuring techniques, and were based on insufficient advance planning and review.

For cost reasons, full-scale aircraft test programs are most often conducted by government laboratories and are usually designed by the operational laboratory; the review and approval process, when it exists, is provided by the next highest level in the agency. Reviewing/approving personnel have many other tasks to perform; further, they are seldom technically current and review therefore is often perfunctory and subjective. It is unusual to have competent pretest peer review and analysis even though such is clearly ithe interest of obtaining maximum results from highly expensive full-scale aircraft fire tests.

Lack of a standardized risk equation based on scenario analysis contributes heavily to potential deficiency of system safety assurance. The major commercial aircraft manufacturing companies, however, are well equipped technically to make recommendations in this regard.

In summary, the committee believes that the lack of an effective integrated methodology for addressing the fire safety aspects of polymeric materials seriously hampers potential progress and inhibits efficient usage of the available funds. Specific chapters of this volume indicate the seriousness of the problem and include recommendations on technical aspects of the problem in relation to aircraft. Because of the overwhelming need for methodology development in all aspects of fire safety performance of materials, the committee also suggested that:

1. A serious effort be made to develop and place into use mathematically based defined fire performance characteristics of polymeric materials.

2. The FAA/NASA/DoD provide a competent pre-event peer review for programs and full-scale tests, or, alternatively, set up inter-laboratory review procedures.

3. The FAA/DoD conduct negotiated procurements on a cost-sharing basis with the major aircraft manufacturers to independently develop proposed standards for:

Risk equation based on scenario analysis

Trade-off equations and constants as the basis for optimizing computer runs on safety assurance

Aircraft system fire performance, including smoke, toxicity and other prototype behavior

Incentives for public safety enhancement above the regulated floor.

AFTERWORD

Following the receipt and implementation of the above mentioned proposals, the FAA, using technical advisors as appropriate, should analyze and develop from them proposed regulations to be promulgated in the normal way, in each specific area.

Communications

The existing methods and modes of communication relating to use of polymers in aircraft are typical of fractionated-crossgrained type structures. There is no technical discipline, either functional or system oriented that is applicable. While there are failure analysis methods and safety reviews made by aircraft manufacturers, these too, do not relate to early and effective communications. Analysis of the airplane system, from a fire safety viewpoint, is seldom adequate to prevent system design deficiencies.

There are a number of potential material problems in aircraft in an emergent status. In general, these have been identified by an investigator or laboratory, but have not been investigated or analyzed in depth. In some cases, the potential problem has not been defined in writing but has been discussed orally in large meetings with consequent developing misunderstanding. Under some circumstances, the full weight of technical knowledge is not brought to bear on the problems. Indeed, the problem is often not understood by those receiving oral and often conflicting reports.

New information concerning polymeric materials has provided warnings concerning deficiencies of certain materials in specified uses. Promulgation of information to the technical community should follow as soon as responsible investigators have reached conclusions. Early warnings to the technical community and open discussion thereof would foster early determination of public safety requirements and potential reductions in aircraft costs by early termination of the use of deficient materials.

A large amount of new information and data are being generated in various agencies and laboratories. Much of it is fragmentary, not fully supported, and in some cases contrary to previously published and accepted data. While this is not a new phenomenon, it bears so heavily on public safety that early evaluation is highly desirable.

Under such circumstances, it appears that a communication system should be developed to provide:

Early identification and description of emerging system material design problems using a standardized format.*

Early warning of identified material deficiencies using a standardized format.*

*Perhaps including (1) an identification and definition of the problem/deficiency; (2) an indication of the agency, laboratory or investigator involved (including location); (3) a "guestimate" as to the potential consequences of the problem/deficiency; (4) an indication of what agency, and project under which it falls or, if no work is being accomplished, what should be done; and (5) a suggested program for solution.

Early evaluation of new developments, new concepts, and new materials.

A locus to receive, categories and maintain their inventory of information.

A panel of technical experts to accept the data and evaluate the arguments presented by the system for early identification, early warning and evaluation and to provide advisory opinions as to action recommended to operating agencies (regulatory bodies, manufacturers, sponsoring agencies, etc.).

Establishment of such a communication system would require a central activity for receipt, transmittal, storage and retrieval, synopsis and analysis of information. The central activity also would monitor the communication network and methodology, making necessary changes as the needs of the users gradually changed with the development of new categories of problems.

It is envisioned that this operation would utilize to the maximum, the cataloging, digesting, publicizing and retrieval system such as those of the Library of Congress, Smithsonian, RANN, commercial activities, etc. No duplication of or interference with those activities should be allowed. The new operation would serve as a focusing device to aid in early solution of fire safety problems relating to aircraft. It is significant that such solutions may have a wide application to other systems in our society (trains, subways, buses, ships, etc.).

Regulation

The airlines, so far, have been required to meet reasonable regulations. Except for early mail subsidies and minor federal airline support, the air transportation system operates under the assumption that it will be self-supporting. The service, speed, and safety have improved continuously as aircraft manufacturers and operators have applied the most recent technological advances. Close relationship of the aerospace-defense efforts and commercial aircraft development has permitted many advances.

The current spate of proposed regulatory legislation should therefore require careful review and consideration. There is no real basis or need to proceed without considering the capability and/or cost in obtaining such action.

In connection with fire safety, the technical basis is sparce and experts disagree sharply about what is safest under normal conditions. When emergencies or other aberrant conditions are postulated, the disagreements increase and intensify because of inadequate, insufficient test data and the lack of commonly accepted risk assessment methods.

The committee strongly believes that progress is being made to reduce the deficiencies to data and methodology; it believes that if its suggestions are implemented, progress will accelerate and satisfy the public needs.

Pending such implementation and the results thereof, the committee strongly recommends utmost caution in regard to legislation affecting fire safety, smoke, and toxicity in commercial aircraft.

AFTERWORD

Equally, the committee strongly recommends to the FAA that it continue and expand its present policy with regard to regulation based on technically supportable data as well as implementing the applicable recommendations in this report.

APPENDIX A

SUMMARY OF AIRCRAFT RAMP,

IN-FLIGHT, AND POST-CRASH FIRES

TABLE A-1 Ramp Fires Summary: U.S. Air Carriers, 1959-73

Source Category	Number Reported	Percent
Electrical	22	33.8
Oxygen Servicing	11	16.9
Fuel Leaks	4	6.2
Engines	3	4.6
Maintenance	3	4.6
Misc. or Unknown	19	29.3
Total	62	100.0

TABLE A-2 Ramp Fires Summary: Military (Navy, 1960-73; Air Force, 1968-74)

Source Category	Navy		Air Force	
	Number Reported	Percent	Number Reported	Percent
Fueling Procedures	26	32.5	2	28.6
Engine	13	16.3	0	0
Electrical	12	15.0	0	0
Hydraulics	9	11.3	0	0
Ordnance Explosions	5	6.3	3	42.8
Misc.	15	18.6	2	28.6
Total	80	100.0	7	100.0

TABLE A-3 In-Flight Fires Summary: U.S. Air Carriers, 1959-73

Source Category	Number Reported	Percent
Galley	94	55.6
Engine	25	14.8
Electrical	18	10.6
Cigarettes	11	6.5
Oxygen System	2	1.2
Airframe Failure	2	1.2
Misc. or Unknown	17	10.1
Total	169	100.0

TABLE A-4 Breakdown of In-Flight Galley Fire Incidents: U.S. Air Carriers, 1959-73

Source Category	Number Reported	Percent
Food	33	35.9
Electrical	17	18.6
Grease	9	9.8
Coffee Maker	6	6.5
Fan Motor	6	6.5
Water Pump	4	4.3
Refrigerator	4	4.3
Papers	4	4.3
Plastics	3	3.3
Misc.	6	6.5
Total	92	100.0

TABLE A-5 In-Flight Fires Summary: Military (Navy, 1959-73; Air Force, 1968-73)

Source Category	Navy		Air Force	
	Number Reported	Percent	Number Reported	Percent
Engine	80	54.4	2	28.6
Fuel Leak	32	21.8	2	28.6
Electrical	6	4.1	0	0.0
Hydraulics	6	4.1	0	0.0
Ordnance Explosions	6	4.1	3	42.8
Misc.	17	11.5	0	0.0
Total	147	100.0	7	100.0

TABLE A-6 Post Crash Fires Summary: U.S. Air Carriers, 1959-73

Source Category	Number Reported	Percent
Aborted Take Offs	13	33.3
Landing Short	12	30.8
Engine	4	10.3
Gear Failure	2	5.1
Hard Landing	2	5.1
Misc, and Unknown	6	15.4
Total	39	100.0

TABLE A-7 Post Crash Fires Summary: Military (Navy, 1959-73; Air Force 1968-73)

Source Category	Navy		Air Force	
	Number Reported	Percent	Number Reported	Percent
Tire Failures	4	17.5	3	4.0
Arresting Gear	0	0.0	0	0.0
Not Engaged	3	13.0	0	0.0
Hard Landing	3	13.0	4	5.3
Struck Aircraft on	0	0.0	0	0.0
Deck (or Collision)	3	13.0	6	7.9
Landed Short (or Long)	2	8.7	18	23.7
Misc.	8	34.8	11	14.5
Engine Malfunctions			19	25.0
Out of Control on Ground			10	13.2
Gear Failure			5	6.6
	23	100.0	76	100.0

APPENDIX B

MATERIAL FIRE LOAD DATA

TABLE B-1 Heats of Combustion for Typical Materials Found in Aircraft Passenger Cabins

Material	Combustion Heat BTU/lb.
Rayon	6,700
Tobacco	6,800
Cotton	7,100
Acetate	7,700
Polyvinyl/Chloride	7,700
Triacetate	7,800
Wood	8,800
Wool	9,000
Polyester	9,300
Mod Acrylic	11,000
Unsaturated polyester	13,000
Nylon 6	13,000
Spandex	14,000
Foam rubber	15,000
Bituminous coal	15,000
Urethane	16,000
Polystyrene	18,000
No. 6 fuel oil	18,000
Butadiene/styrene copolymer	19,000
No. 1 fuel oil	20,000
Polyethylene	20,000
Natural gas (MW=20)	23,000

TABLE B-2 Part 25 -- Typical Construction

Element	Area or Number	Unit wt or lb/ft^2	Wt/AC
Part 25 Manufacturer Selected			
Window belt panels	1,937	0.7	1,356
Entry panels	327	0.5	164
Ceiling Side	700	0.5	350
Ceiling center	480	0.5	240
Ceiling drop	425	0.6	255
Overhead stowage	1,680	0.5	840
Partitions & doors	95	0.7	67
Windows	180	6.0	1,080
Window shades	120	(0.5 ea)	60
Floor covering	2,245	0.4	898
Cargo liner & galley	1,947	0.3	585
Floor core	2,245	0.5	1,122
Lavatories	777	0.7	544
Insulations(30% 2000 lb)			600
Coat rooms, etc.	400	0.5	200
Total			8,361
Part 25 Airline Selected			
Galley modules & charts			
Excl. metal parts	--	--	2,450
Incl. metal parts	--	--	4,500
Seats (at 32.5)			
Excl. metal parts	--	--	3,510
Incl. metal parts	--	--	8,775
			19,235

Part 121 Service & Galley Supplies*

Cabin Service supplies (2.47 lbs)		270 = 667
Galley Supplies	(3.305 avg.)	270 = 892
		1,559

Passenger Carry On

Coats & luggage est. (12 lbs/PAX) 270 = 3,240

TABLE B-3 Combustible Summary

	Wt.	% Total
Part 25 mfg.	8,361	43.7
Part 25 airline	5,960	31.2
Part 121 service & galley (airline)	1,559	8.2
Passenger carry on	3,240	16.9
Subtotal	19,120	100.0

*See Table B-4 for detailed breakdown.

TABLE B-4 Part 121 Service and Galley Supplies Breakdown

Type	Weight per passenger (lb)
Cabin Supplies	
In Lavatories	
Kleenex and TP	0.02
Sanitary napkins	0.01
Towels	0.12
Miscellaneous	0.05
	0.20
Seats	
Headrest covers	0.09
Newspapers	0.16
Sickness bags	0.07
Literature set	0.54
	0.87
Cabin	
Clipboards	0.01
Baby kits	0.17
Coat hangers	0.16
Magazines	0.14
Magazine binders	0.16
Picture books	0.02
Paper cups	0.03
Whisks	0.01
Attendent misc.	0.20
	0.90
Blankets and Pillows	0.50
	1.40
Subtotal	2.47
Galley Supplies	
Preset Tray Less Food	2.05 - 3.25
Preset Snack Tray Less Food	0.56 - 0.66
Beverage Serving Glass	0.04 - 0.05
	2.65 - 3.96
Average	3.305

APPENDIX C

FIRE AND SMOKE

DETECTION AND CONTROL SYSTEMS

C.1. Fire and Smoke Detection Systems

Many aircraft utilize some type of thermal sensor (either unit or continuous element type) for detecting fire and overheat conditions. Most of the older military aircraft (C-54, C-97, B-52, KC-135) use the unit detector that consists of a bi-metallic switch which completes an electrical circuit triggering an alarm when a particular temperature is exceeded. These systems are inherently limited in that they only provide coverage of a very small area. The false-warning problem has been so acute with this system that it has been deactivated or significantly reduced in some aircraft.

The remainder of operational USAF aircraft have fire detection systems that use a continuous element cable. This system provides much greater detection coverage than the unit detector if properly installed in the necelle. The continuous cable consists of two electrical conductors, one a tubular dual-wall outer sheath and the other a wire in the center of the tube. The two conductors are separated by a compacted semi-conductor filler material whose resistance varies as a function of temperature. When a preselected temperature with a voltage potential on the conductor is reached, sufficient current will flow in the electrical circuit to cause an alarm. Fire detection systems of this type all have the same reliability problem in that they are susceptible to false warnings due to electrical shorts. The use of a short descriminator in the electrical circuit of some systems (i.e., C-5A and F-111 aircraft) has significantly reduced this problem; however, it does not eliminate false warnings from partial short conditions.

The problem of false warnings can be significantly reduced or eliminated either by using systems that operate on entirely different principles which are inherently reliable or by using redundant or backup components with the conventional system to increase its reliability. The dual loop overheat system used on many of the commercial aircraft today is an outgrowth of the redundancy features of the integrated fire and overheat detection system conceived by the USAF in the early 1960's. This system as well as the self-generating and time domain reflectometry overheat detection systems, have or been or are being developed. Each of these systems should substantially reduce the false warning problem.

Recently completed was the development of a self-generating over-heat detection system that utilized a sensing cable which is essentially a continuous thermocouple. False warnings should not be a problem with this system since the ambient temperature level must reach the alarm temperature in order to generate the voltage required to provide the alarm. Alarm settings for the system can be varied by proper selection of the sensor filled material and by changing the setting in the control box. In addition to not being prone to false warnings, the system offers an additional advantage over a conventional system in that it can detect a fire when the sensor is broken or damaged. The self-generating system has been fully qualified to Mil-Std-810B and is now being subjected to flight tests on an FAA Convair 880. A combined total of 600-fault-free hours have been compiled on the systems. These

systems have received no maintenance since installation but are being monitored continually and checked before, during, and after each flight by the flight engineer.

Another fire detection system concept employs an electrical transmission line for the detection of a fire or overheat condition. The prototype system developed for the Air Force utilizes a coaxial cable which changes its electrical properties drastically as a predetermined temperature is reached. System operation is achieved by sending short duration electrical pulses alternately from both ends of a coaxial cable. When the predetermined or alarm temperature is reached, the electrical pulses are reflected (but in opposite polarity) by the overheat section back to the detector at the end of the cabin.

The present prototype system is limited to cable lengths of 50 feet, but it is expected that if a more optimum cable material is developed, usual cable lengths of up to 250 feet will be possible. With this capability, the system would be extremely attractive as an overheat detection and location information system for such applications as aircraft electronic and cargo bays and long hot bleed air ducts in wings. In addition, a single TDR overheat detection system could provide coverage for more than one engine, thus reducing the weight and cost of the detection system in aircraft. The present prototype TDR system has not been qualified to Mil-Std-810B. The cable presently being used is flight qualified.

The inability of current fire detection systems to detect all engine nacelle fires has been a problem. The problem simply stated is that the detection systems used to date do not and cannot provide 100 percent coverage for the area to be protected. These symptoms provide point or linear coverage only. The Air Force has concluded that the problem of missed fires can be reduced only to an "acceptable" level or eliminated entirely by using detection systems that have sensors which provide 100 percent or volume coverage of the area to be protected. After considerable study over the years of various techniques and hardware, it has been concluded that radiation sensors are the only devices known at the present time which meet this criteria These senosrs, depending upon the type, respond to a particular segment of the radiation spectra emitted from the combustion process while discriminating against background radiation (i.e., solar radiation, artificial lighting, sparks, or a hot body in view of the detector). Response times of radiation sensors can be orders of magnitude faster than those of thermal sensors (a few milliseconds vs. seconds to minutes for the thermal detector).

Two ultraviolet senors have recently been developed for the Air Force, one capable of operating in a 500°F (260°C) environment and the other in a 1,000°F (538°C) environment, by Thomas A. Edison and the General Electric Company. Tyco Laboratories developed an infrared sensor capable of operating in a 750°F (399°C) environment with a 1,000°F (538°C) background. All of these sensors meet the military specification requirements for aircraft fire detection.

Other infrared and ultraviolet sensors have been or are being developed by various manufacturers and should be adequate for the engine nacelle environment assuming the environmental temperatures are compatible. Thomas A. Edison and

Honeywell, Inc., manufacture ultraviolet sensors capable of operating in a 500°F (260°C) aircraft environment. These sensors have been used in various commercial applications for several years, demonstrating a high degree of reliability. A flight system utilizing the Honeywell sensor has been fabricated and successfully flight tested by the FAA for the Air Force on an FAA Convair 880 aircraft. The 500°F (260°C) Edison ultraviolet sensor is being developed for the Air Force (AFAPL). Fenwal, Inc. (Ashland, Massachusetts), is in the final stages of development of an ultraviolet fire detection system for aircraft usage. This system is limited to a maximum ambient temperature of 250°F (121°C) but can probably meet the requirements of most present day aircraft engine nacelles by judicious placement of the sensors or by providing for sensor cooling. Helicopter requirements also could be met by this system. This system has been subjected to Mil-Std-810B and is currently undergoing flight testing at the FAA/NAFEC on a CV-880 aircraft.

The AFAPL is in the final stages of development of the integrated fire and overheat deteciton system that should provide optimum performance and reliability for engine nacelle applications where overheat and fire are potential problems. Thomas A. Edison is conducting the development of this flight-qualifiable system which consists of six radiation-type detector heads (each containing two ultraviolet sensors and a test source), dual loop overheat sensors, a crew readout unit, a computer control unit, and maintenance warning unit. The system uses separate sensors for overheat and fire detection. Overheat detection is provided by conventional dual loop continuous overheat cables while fire detection is provided by the Thomas A. Edison Mark II ultraviolet sensors which are capable of 500°F (260°C) continuous operation.

The AFAPL is nearing completion of the development of a smoke detection system for a cargo aircraft such as the C-5A. This smoke detector is an open-path forward-scattering optical system that can discriminate smoke from other background particulates such as water vapor, dust and cigarette smoke. This system overcomes the primary problem inherent with most present day smoke detectors – i.e., the system monitors an area or volume and does not require the smoke particulates to enter the detector (as in the case ofr ionization detectors for example). At the present time, three flight prototype systems are being built for flight testing and further laboratory evaluation.

Minimum detection requirements for cargo and baggage compartment in the U.S. air carrier aircraft are prescribed in FAR 25.857 which specifies that a separate smoke detector or fire detector system is required for Class B, C, and E compartments to give warning at the pilot or flight engineer station. A Class B cargo or baggage compartment is one in which there is sufficient access in flight to enable a crew member to fight a fire in any part of the compartment with a hand fire extinguisher. A Class C compartment is one that includes a built-in fire extinguishing system controllable from the pilot or flight engineer station, while a Class E compartment is one used only to carry cargo. Design must provide that these compartments exclude hazardous quantities of smoke, flames, and noxious gases

from crew and passenger compartments and that ventilating airflow be controlled within the compartments. Examples of the application of the FAR 25 requirements are shown in schematically in Figure 7, page 58, for two types of wide-body jet aircraft — an all-passenger version and an all cargo version.

Four smoke detectors are installed in the forward and center/aft cargo compartments. Three of the four detectors in the center/aft compartment are installed in the center compartment area and one within the aft compartment area. All lower cargo smoke detectors are installed in the compartment ceiling within recessed panels that include the firex discharge nozzles. Each smoke detector incorporates its own amplifier. In addition to the smoke detector installation, two heat detectors are shown installed in the ventilation exit ducts of the ventilated aft compartment area. (Installation of the heat detectors at this location is not an FAR 25 requirement.) The detector installation for the all cargo configuration (Figure 7, p. 58) shown consists of eight smoke detectors located throughout the cabin. For convertible cargo aircraft, the main cabin is deactivated for passenger use and access is provided to each compartment for fire fighting procedures.

Detectors are located to provide for safe use of the aircraft with one detector inoperative. The warning system that will actuate from any one of the smoke (or heat detectors and the associated cockpit indicators are discussed and illustrated below.

The detection system requires human monitors at the flight station to observe the various warning indicators. Thus, when the flight station is not manned, the detection system is not functional. This condition occurs frequently when the plane is parked or left at the ramp. It appears that a modification to the detection system to provide off-plane monitoring would be most useful. This might take the form of a plug-in device similar to those in use for supplying power, etc. New wide-bodied jets (B-747, L-1011, DC-10) have multiplex systems installed that are particularly adaptable to this concept.

The flight engineer's panel for the vehicle configuration with lower cargo protection consists of two (amber) Firex agent low lights, eight (amber) smoke detector test lights, one (amber) overheat detector test light one (red) forward cargo fire warning light, one (red) center/aft cargo fire warning light, two agent discharge switches, one agent compartment selector switch, and one cargo fire test and arm switch (Figure C-1). Actuation of any of the heat or smoke detectors will result in the following cockpit indications:

1. Forward cargo fire or center/aft cargo fire warning light will illuminate (R) (flight engineer's panel).
2. Cargo fire warning light will illuminate (R) (pilot's annunciator panel).
3. Master warning lights will illuminate (R) (pilot's, copilot's and flight engineer's panels).
4. Detector test light(s) will illuminate (A) (flight engineer's panel).

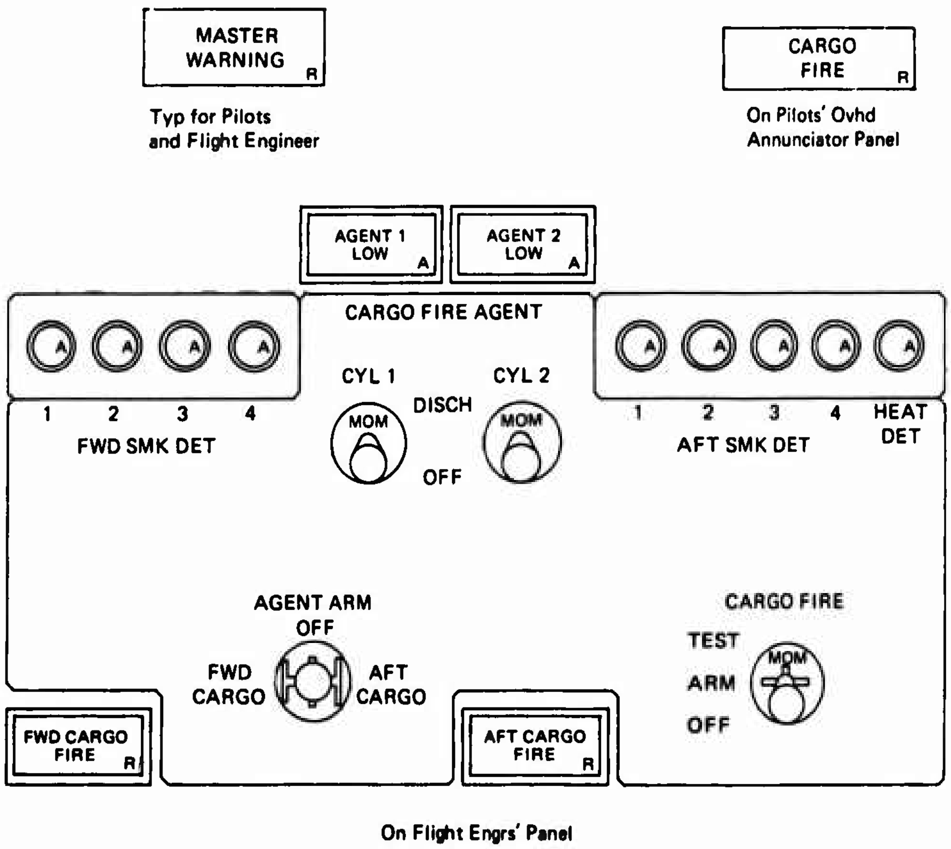

MASTER WARNING R
Typ for Pilots and Flight Engineer
CARGO FIRE R
On Pilots' Ovhd Annunciator Panel
AGENT 1 LOW A
AGENT 2 LOW A
CARGO FIRE AGENT
CYL 1
CYL 2
DISCH
OFF
MOM
MOM
1 2 3 4
FWD SMK DET
1 2 3 4
AFT SMK DET
HEAT DET
AGENT ARM
OFF
FWD CARGO
AFT CARGO
CARGO FIRE
TEST
ARM
OFF
MOM
FWD CARGO FIRE R
AFT CARGO FIRE R
On Flight Engrs' Panel

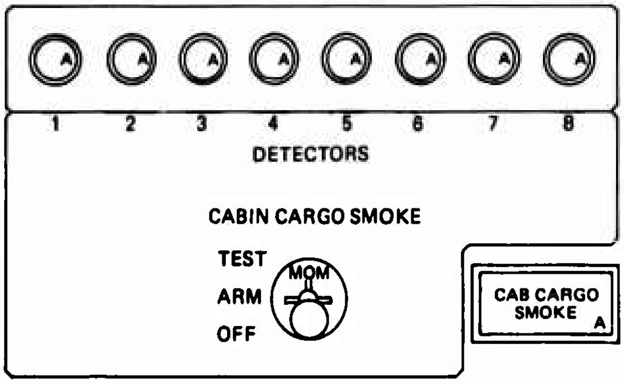
Figure C-1.

The flight engineer's panel for the main cabin cargo configuration consists of eight amber smoke detector test lights, one amber cabin cargo smoke caution light, and one cargo smoke test and arm switch (Figure C-2). Actuation of any one of the smoke detectors will result in the following cockpit indication:

1. Cabin cargo smoke caution light will illuminate (A) (flight engineer's panel).
2. Master caution lights will illuminate (A) (pilot's, copilot's, and flight engineer's panels).
3. Cabin cargo smoke caution light will illuminate (A) (pilot's annunciator panel.
4. Detector test light(s) will illuminate (A) (flight engineer's panel).

Typ for Pilots
and Flight Engineer

On Pilots' Ovhd
Annunciator Panel



On Flt Engineers' Panel

C.2 Control of Fires

As indicated in Fig. 7, p. 58, two hermetically sealed Firex (bromotrifluoromethane – CF_3B^2) containers, with two discharge heads and two cartridges installed in the electrical power center, will either discharge the agent to the forward cargo compartment or to the center/aft cargo compartment of a wide-bodied jet.

The two-container installation provides an initial discharge of 105 pounds of agent into the compartment with a make-up shop of 60 pounds approximately one hour later. In addition, the actuation of the fire agent compartment selector switch (to the center/aft position) prior to agent discharge, automatically shuts off the

ventilation to the aft compartment are (due to the lack of airflow) and the ventilation entrance louvers close, thereby isolating the center/aft cargo compartment. Aircraft operating manuals require the compartment selector switch to remain in the center/aft position once selected and the aft cargo compartment switch to be shut off. The ventilation shutoff valve is a fail "closed" valve configuration to ensure no ventilation under the fire condition.

Ventilation of the aft compartment area is normally controlled by the vent switch on the flight engineer's panel. (This switch also will be put in the off position during the clean-up procedure after a center/aft compartment fire).[3] Ventilation exhaust from the center/aft cargo compartment is ducted to the outflow valve to prevent agent or smcke from entering the cabin. Airflow cut-off to cargo compartments in the event of fire is an active concept to extinguish a fire.

A test program is being conducted by the FAA to evaluate the fire extinguishment characteristics of a Halon 1301 (bromotrifluoromethane) fire suppression system in the passenger cabin of a commercial air transport. Halon 1301, is a colorless, odorless gas stored as a liquid in a pressurized container and has low toxicity in the concentration required for Class A fire extinguishment. Two agent dispersal systems located at the ceiling are being evaluated: modular and perforated tube. The program is divided into three phases: (1) comparison of discharge and inerting characteristics and no-fire conditions; (2) automatic extinguishment of typical cabin fires; and (3) determination of protection against an external fuel fire adjacent to a fuselage rupture. The first phase has been completed and consisted of 16 tests in a DC-7 passenger cabiwhere measurements were continuously made of agent concentration at 20 locations, as well as temperature, pressure, noise, and visibility. It was demonstrated that a relatively homogeneous extinguishing concentration could be rapidly achieved throughout the passenger cabin, including hidden areas in the lavatories, galleys, or beneath passenger seats. A slight agent stratification is formed initially and becomes more pronounced with time, depending on the removal rate of agent from the cabin. The effect of open emergency exits before or after agent release does not noticeably affect the rapid attainment of an extinguishing concentration but will control the time an inerting concentration can be maintained. With open exits, the loss of agent concentration begins at the ceiling and increases with time toward the direction of the floor uniformly along the fuselage length. Both the modular and the perforated tube dispersal systems are safe, efficient and effective. An assessment should be made of all the problems associated with the use of Halon 1301, with emphasis on hazards of decomposition products, under full-scale cabin fire conditions and the findings of such tests should be evaluated in view of the hazards of an uncontrolled cabin fire.

Gassman investigated the effectiveness of a Halon 1301 fire suppression system in a 5,000-cubic-foot C-130 cargo compartment which was loaded to 50 percent by volume. One hundred pounds of Halon 1301 were discharged into the compartment upon detection of fire and ventilation shutoff. This test indicated that a fire suppression system can prevent the occurrence of a flash fire which

occurred with a 50 percent load fire test when only the ventilation was shut off and also provided for a significant reduction in the maximum ambient temperature which is reached ithe cargo compartment duiing a fire (350°F vs. 1,800°F).

Gassman and Hill further evaluated a Halon 1301 fire suppression system in a C-130 cargo compartment and concluded that a 3 to 5 volume percent concentration and ventilation shutoff can effectively control cargo compartment fires.[2] Two tests were also conducted to determine the effectiveness of liquid nitrogen as an extinguishing agent. These tests revealed that liquid nitrogen is an effective extinguishant provided that the amount used, when in the gaseous state, is equal to 75 percent of the gross volume of the compartment.

A Halon 1301 fire suppression system is being installed in Air Force C-5A transport aircraft on a retrofit basis. The Halon 1301 fire suppression system is a part of the C-5A fire protection system which also includes a liquid nitrogen fuel tank inerting system and liquid nitrogen fire-fighting system. The fire suppression system is a modular type consisting of 19 spherical extinguishers, each containing 70 pounds of Halon 1301, and one extinguisher containing 10 pounds of Halon 1301 to protect the cargo compartment, avionics and guidance bay, and center wing section. The number of extinguishers discharged into the cargo compartment depends upon the volume of cargo being carried.

The liquid nitrogen firefighting system directs liquid nitrogen from the fuel tank inerting system dewar vessels into the cargo compartment under-floor areas, wheel wells, power transfer unit compartments, wing dry bays, and wing and plylon leading edges. Venting areas in several of these zones were enlarged to compensate for increased pressure when nitrogen is discharged. The quantity of nitrogen discharged into each zone is established by a timing device as a function of the zone volume to assure that nitrogen is not wasted.

The locating of flame arrestor material in the fuel tank is another technique for preventing or reducing combustion overpressure in the ullage of aircraft fuel tanks. Reticulated polyurethane foam, as the arrestor material, has been used in military designs for several years. Both fully packed and gross voided applications have been successful.

The fuel tank ullage explosion hazard with hydrocarbon fuels involves a small delay time from initial ignition to attainment of a damaging overpressure condition due to combustion. If combustion reaction can be quenched rapidly enough to prevent pressure increase above the damage threshold limit of the containing structure, an effective means for explosion protection would be available. In the case of aircraft fuel tannks, suppression action by this means generally must be sufficiently rapid to limit combustion overpressure below 3 to 5 psi. The critical time for such action with a single point ignition source, such as an electric spark, is less than 20 msec. Explosion suppression systems based on the above action are presently available and are being utilized for industrial and aircraft fuel system explosion protection applications. These systems employ sensors that are very sensitive to the radiation emitted from the combustion process and provide for the automatic activation

of a suppressor containing a suitable halogenated hydrocarbon (halon) extinguishing agent. The agent is discharged with sufficient force to rapidly quench the combustion reaction while it is still in the incipient stage. Overall response time for these systems from ignition of the fuel-air mixture to discharge of suppressant is 10 to 20 msec. Performance of existing systems is adequate for the single-point ignition source but inadequate for the multi point ignition condition associated with military applications. The typical aircraft weight penalty associated with this type of system is approximately 0.3 pounds per cubic foot of protected volume; the associated fuel displacement penalty is negligible.

C-3 References

1. Glassman, J.J. *Characteristics of Fire in Large Cargo Aircraft (Phase II).* Federal Aviation Administration Report FAA-RD-70-42. Springfield, Va.: National Technical Information Service, 1970.

2. Glassman, J. J., and Hill, R. C. *Fire Extinguishing Methods for New Passenger/Cargo Aircraft.* Federal Aviation Administration Report FAA-RD-71-68. Springfield, Va.: National Technical Information Service, 1971.

3. Sarkos, C.P. *On-Board Aircraft Cabin Protection Systems.* National Fire Protection Association Aviation Bulletin No. 398. NFPA, 1973.

APPENDIX D

POST-FIRE INITIATION CONSIDERATIONS

D.1 Fire Location and Type

An analysis of fire accidents involving world wide U.S. air carriers between 1959 and 1973 indicates a variety of ignition sources, that, when in consort with the fire loads present in aircraft, provide the potential for fire in varied locations throughout the aircraft. Engines, food service areas, electrical wiring and components, cigarettes, and oxygen system servicing appear to have the greatest potential for ignition.

The type of fire that results from a given ignition source is determined by the adjacent material and the type and magnitude of the fire load available to support its development. Ignition sources may develop smoldering fires or hot, flaming fires; thus, a full spectrum of possibilities exist even without the ignition of "jet propulsion fuel" from a post-crash development fire.

A compilation of the ignition source and subsequent fire damage consequences of several worldwide U.S. air carrier fire accidents have been tabulated by fire hazard mode category and are shown in Tables D-1 to D-3.

D.2. Design, Operation, and Procedures for Handling Emergencies

Emergency procedures for civil and military transport aircraft form a basic part of the vehicle fire safety systems. The procedures necessary for personnel and passenger safety during the post-ignition phase of an incident are applicable to all three of the fire hazard mode situations described in Chapter 4. Details of the procedures are discussed below.

D.2.1. Civil Aircraft

D.2.1.1 FAA Design and Construction Requirements

Requirements for emergency provisions which are applicable to the certification of new transport aircraft are included in the following airworthiness standards of Part 25 of the Federal Aviation Regulations (FAR) issued by the Federal Aviation Administration, Department of Transportation, under Title 14, Code of Federal Regulations (14 CFR), Chapter 1:

FAR 25.8-1 – Ditching
FAR 25.803 – Emergency Evacuation
FAR 25.805 – Flight Crew Emergency Exits
FAR 25.807 – Passenger Emergencv Exits
FAR 25.809 – Emergency Exit Arrangements
FAR 25.811 – Emergency Exit Marking
FAR 25.812 – Emergency Lighting
FAR 25.813 – Emergency Exit Access
FAR 25-1414 – Ditching Equipment

These emergency evacuation standards require provision of emergency exits, escape slides, emergency exit markings and locator signs, exit passageways, and other features to assist and direct passengers quickly out of the airplane. FAR

TABLE D-1 Category I (Ground Fires) World Wide (U.S. Air Carriers), 1959-73

Date	Ignition Source	Progress Damage
2-21-61	Arcing of phenolic toilet flushing motor terminal board	Haze seen when air-conditioning unit turned on (filled fuselage) then fire visible; interior gutted
3-1-61	Cigarette into cleaning supplies basket (?)	Interior bad (mainly ceiling areas) removal of oxygen bottles by fire fighters helped (from rear door to main door)
6-15-61	Collapsed rotating nose landing gear started fire in electronics compartment	Fire spread to forward compartment and into crew compartment in 20 minutes, then first two rows of passenger seats involved
10-18-61	Matches	Set fire to plastic grating; smoldering fire on rug and in plastic overhead-charred seat cover
5-28-62	Electric wiring around razor outlet-(lavatory)	Lint and paper and lavatory walls near outlet burned; extensive fire in lavatory
12-1-62	Crew were checking oxygen system-started near oxygen system pressure reducer (?)	Fuselage gutted
5-30-63	Unknown; (two "suspected" causes):-sparks from another taxiing aircraft into open cargo or cabin doors/short circuit in aft lavatory	Interior gutted; failure of floor between cargo and cabin but no unusual cargo and apparently fire started in cabin
8-8-63	Cigarette in market bag used to empty ash tray	Bag on seat smoldered on seat; hold in seat cover

10-27-63	Cigarette or electric wiring	Damage to rug, return air grille near seats, fire stop, and air ducting; flames as high as overhead rack; cabin filled with smoke and evacuation ordered
11-16-63	Opening oxygen valve in cockpit	Cutting torch-like action burned through fuelage skin; extensive damage around valve; smoke damage in interior
12-3163	Wire ground to case	Small flame at cabin heater; heater case and wiring damaged
1-4-64	Reading light out of receptacle and shorted between light switch and oxygen mask door release spring	Small burned area on oxygen mask box
11-24-65	Cleaning with flammable fluid (electrical power on) (?)	Flash fire; fuselage destroyed--top and bottom burned through; one dead evacuating (seats and carpet were removed
2-13-66	No data	Minor damage
3-12-66	Electrical connector in galley--(fault created by water penetration	Damage to electric wiring and insulation above galley floor area and to window area; some cabin lining burned; smoke damage
12-31-66	Static-cleaning fluid (no electric power) aliphatic naptha	Rag burst into flames; plastic lining involved; damage to seats not serious; paper runner on floor not involved; cabin vinyl lining reason for rapid spread of fire and heavy smoke; structural damage (no oxygen involvement; bled and purged before fire)

6-13-67	Unknown - muffled explosion	Fire started in forward compartment; oxygen bottles (3' x 114 ft.) had ruptured in lower cargo compartment increasing intensity of fire; burned 3-foot hole in floor over bottles
10-9-67	Battery charger	Electrical equipment compartment fire
10-17-67	Battery charger (?)	Flame in lower electrical equipment compartment
6-19-68	Battery electrolyte spill	?
9-7-68	Recharging crew oxygen system--hydraulic oil in line (?)	Total loss
1-25-69	Charging oxygen system-piping fire-organic or material (?)	Quick burn through of aircraft; 2-foot hole in skin near forward cargo compartment; floor beams damaged and wiring and cables destroyed in vicinity; one seat back burned and cushion and adjacent rug scorched; extensive smoke damage
8-7-69	Short circuit--wet razor outlet ignited paper	Spread up to overhead ceiling area then forward to wing and down to ceiling panels; then flash fire; interior badly damaged
10-10-69	Electric wire overload (c-b too large)	Fire in overhead paneling area 4 by 8 feet burned
1-27-70	Three packs of matches-in pocket of hostess smock thrown on rack-friction	Smock folded so fire suppressed
4-22-70	Cove light capacitor (?)	Almost all cabin burned out
6-7-70	Oxygen	Oxygen hose burned at seat; smoke in aft cabin

12-31-70	Oxygen	Oxygen service panel fire; hole burned in floor above panel causing fire and smoke damage to interior
12-31-70	Charging oxygen system	Bright flash then rapidly spreading; extensive damage especially in cockpit (principally smoke in cabin area)
9-4-71	Lighting control switch	Smoke and flames from cabin attendant control panel; approximately 50 wires burned to extent little or no insulation remained.
1-25-72	Malfunctioning of recirculating unit (defect in circuitry) allowed heating unit to stay on when blower not operating	Fire in circulating air unit area, wiring compartment overhead, floor of cabin above unit; extensive smoke damage in all cabin area
3-2-72	Rotary switch	Stewardess' service panel smoke; damage to four terminals and switch wiring.
3-15-72	Walk around oxygen bottle	Two passenger seats, hat rack, and side panel scorched
3-28-72	Oxygen line rupture	Flames from sidewall 3-foot-suare area above observers seat; severe heat and smoke damage; wiring damage
4-18-72	Lighting transformer	Flash and shower of sparks overhead; hole burned on trough lighting transformer
5-1-172	Faulty electrical fixture behind cabin lining	Substantial portion of interior burned; burned through fuselage in places
5-27-72	Wires short at terminal strip	Electrical compartment flame; APU generator power wires burned

6-10172	Walk around oxygen bottle (oil contamination)	Seat back and cushion involved; rug section replaced
8-29-72	Oxygen system shutoff valve	Heavy smoke and flames through ventilation; shutoff valve fire; only damage to insulation blanket and panel
3-17-73	Wiring (Casper air fans)	Smoke and sparks emitting from seat MUX cable damaged; 5 minutes later smoke from another seat
3-22-73	Oxygen-oily wool material contacted leaking oxygen	Oxygen fire just aft of cockpit; damage to air-conditioning ducts, electrical plastic conduit, and wiring; smoke and heat damage over almost 200 inches of right side and ceiling
9-24-73	Checking oxygen bottle	50 to 60 percent of cabin and cockpit area burned

NOTE: Data based on private communication, McDonald Douglas Corporation

TABLE D-2 Category II (In-Flight Fires) Worldwide (U.S. Air Carriers), 1959–73

Date	Ignition Source	Progress Damage
9-12-60	Electrical engineer's center forward floor heater shorted internally	Smoke in cockpit; smoke and flames from floor plate 1 foot aft of center pedestal
3-16-61	Electrical fire in lavatory	
3-18-61	Electrical fire in cockpit	
7-29-61	Fire in lower nose section (wheel well) well)	Smoke in flight deck and forward passenger compartments
9-27-61		Fire; total loss; early smoke in fuselage
11-5161	Engine disintegrated turbine blade	Blade scorched hole in carpet; scorched insulation in aft cargo compartment
1-15-62	Passenger dropped cigar on newspapers on floor near exit air grille	Fiberglass resin impregnated grille ignited
4-25-62	Lighted cigarette in return air system	Ignited lint and polyurethane foam insulation and polyester fiberglass grille
2-15-63	Cigarette (?)	Floor level fire; DADO panel burned through; air-conditoning bay burned out behind sidewall; two seats charred
3-7-63		Fire in-flight and impact
6-18-63	Electrical circuits D lavatory charred, wire and insulation burned-moisture (?)	

10-14-63		Flame in floor air return grille
12-21-63		Minor fire in right rear lavatory disposal chute
3-5-64		Lavatory fire; minor damage
6-5-64	Smoke from flight engineer's panel; switch burned	
6-13-64	Electrical fire	Minor damage
10-1-64	Cigarette	Started below seat adjacent to wall; rug burned (8-inch diameter); insulation between floor and ceiling panel burned; still smoldering sound-proofing when cabin liner later removed; luggage compartment smoke filled
11-19-64		Seat cushion smoldering
11-25-64	Electrical fire	Burned wiring and electrical components near basin area behind buffet
1-19-64	Cigarette dropped into food parcel	Minor damage to rug and side panel
3-14-65		Small fire contained in trash can
1-29-66	Windshield heat transformer electrical fire	
10-30-66	Engine disintegrated and ruptured fuselage; started interior fire	

9-1-67	Water into battery charger area	Fire in electrical equipment compartment
9-14-67	Electric wall heating blanket ignited (terminal plate short)	Sparking and smoldering blanket (electric); wires and insulation charred near seat
12-20-67	Static discharge (?)	Electrical fire in windshield heat transformer
7-12-68	Current limiter retention clip problem	Electric sparks overhead right food service door; fire damage to wiring; burned current limiter mounting blocks
9-8-68		Electrical fire behind captain's escape tape panel; wires burned
11-9-68		(?) "Trouble on board", 21 seconds later "Fire on board", 2 minutes later aircraft crashed; traces of fire at rear of cabin found in debris.
11-18-68	Electrical--moisture	Fire in commissary storage area in galley; electric power fuse holder damaged by arcing
11-19-68	"Set" by passenger	Explosion and fire in lavatory
7-26-69		Believed unextinguishable electrical compartment fire; emergency landing attempted; aircraft crashed and burned (4 injured, 33 killed)
1-29-70	Cigarette or match in trash container in lavatory	Plastic top of waste container burned away; container, paint, gasper eyeball hose, and wire bundles charred
1-30-70	Cigarette	Small fire in aft lavatory towel disposal

5-29-70		Trash can fire in aft lavatory; contained
6-25-70	Wire short (charred)	Wires burned and used towel container involved
1-9-71	Cigarette ash	Passenger's purse burst into flames; 3-inch diameter hole melted in adjacent seat
10-16-71	Auto soiler actuator overheat	Smoke in cockpit; flash fire at pedestal
3-31-72	Wire short at terminal strip	Forward cabin electrical panel "fire"
1-5-73	Administering single oxygen cylinder	Fire contained in unit carrying container
2-28-73	Cigarette	Small waste fire in trash container in aft lavatory; contained
8-8-73	Oxygen unit overheat	Oxygen unit flame
9-5-73	Cigarette ignited towel	Small fire and smoke from lavatory refuse compartment; damage only to basin drain overflow lines
9-12-73	Walk around oxygen	Fire
9-13-73	Cigarette (?)	Minor fire in lavatory waste chute; contained
10-25-73	Cigarette and paper toweing	Aft lavatory smoke; fire in paper disposal bin; contained

NOTE: Data based on private communications, McDonald Douglas Corporation

TABLE D-3 Category III (Post-Crash Fires) Worldwide (U.S. Air Carriers), 1959-73

Date	Occupants Fatal	Occupants Total	Accident Narrative Summary	Comments
8-27-59	2	Fatal (another report says 9 occupants; 0 fatalities)	Aircraft crashed 5-1/2 miles from threshold	Total loss; fire after impact
10-19-59	4	8	During recovery from a Dutch Roll, the airplane lost two engines and another caught fire; airplane crashed and separated aft of the wing and the front section burned; survivors were in the aft section	High impact in control cabin and survival impact aft cabin; no exits used (external fire preventing escape in front) evacuated through hole in aft
1-19-61	4	106	Take-off was aborted late; airplane overran the airport, went through the blast fence, and caught fire	Low impact in the passenger cabin and high in the control cabin; flight crew killed
7-11-61	16	122	Airplane swerved on landing; landing gear and engine separated on field discontinuity and the airplane struck a truck; fire and smoke entered through left forward door	Low impact
12-21-61	27	34	Airplane stalled on take-off and fell to earth in a flat attitude from approximately 450 feet, separating just aft of wings; the forward section burned	High vertical impact

6-3-62	130	132	After aborted takeoff, the airplane caught fire after leaving the runway; it crossed a road, went through landing lights, and collided with buildings; two surviving stewardesses were thrown free of the wreckage	High impact; no exits used; external fire prevented escape
8-26-64	0	FATAL	Crash landing; small friction fire outside	Thick smoke in aft section hindered evacuation (fuselage intact); exterior fire extinguished by hand firex
11-23-64	53	73	On aborted takeoff, the No. 4 engine struck a steam roller and caught fire; wing tank(s) exploded shortly after airplane came to rest and airplane was quickly engulfed in flames	Low impact; tank explosions were main factor; extensive fires left no safe exits after explosion
3-14-65	0	FATAL	Aborted takeoff due to engine failure/severed fuel line	Fire at ventral stairs, aft fuselage; extinguished in 1 minute
5-20-65	121	127	Airplane crashed 8 miles from the threshhold; the fuselage was broken into three major sections and widely scattered; onlh the middle section burned; six survivors in aft section	Very high impact; no exits used; fire probably a small factor in deaths
11-8-65	58	62	Airplane landed 1 mile short exploding 4 to 5 seconds after impact; no evidence of anyone attempting to open exits; survivors were thrown from wreckage or crawled through fuselage break.	Very high impact; no exits used; external fire preventing escape

11-11-65	43	91	Both main gears separated at touchdown; right gear ruptured the fuselage and a fuel line and the fuel caught fire (immediate flame thrower) and engulfed the interior	Generally low impact (impact may have been a factor in the forward area)
2-15-66	1	81	At touchdown the airplane struck an approach fence and light; all gears were separated; the fire originated at the right wing and spread to the No. 2 engine; single fatality died later of burns (but fire did not enter cabin for 5 minutes–evacuating?)	Low impact
3-4-66	64	71	Airplane landed short, striking overwater approach lights and sea wall; flight deck and empennage section separated from fuselage; survivors were thrown from wreckage or escaped through holes	High impact; no exits used; external fire prevented escape
7-4-66	2	5	Aircraft stalled 100 feet off runway during takeoff; it cartwheeled twice, separating forward of the wing and cracking forward of the empennage	Deaths were caused by impact in the forward section
8-26-66	5	5	As the airplane took off the left wing dipped, the gear collapsed, and the fuselage struck the ground; flames enveloped the entire airplane	High impact; no exits used; external fire prevented escape

12-24-66	0	FATAL	Landed short and aft section of fuselage separated	Small fire in aft section but no fuel fire outside; quickly extinguished and did not affect evacuation
3-5-67	56	90	Hard landing; fire in mid-cabin shortly after aircraft came to rest; entered when overwing exit fell out or through ruptured floor-chimney effect toward rear	High impact
11-6-67	1	FATAL	Aborted takeoff; fuselage broke in two, gear collapsed	Destroyed on airport
11-20-67	69	82	Hit trees on landing; only tail intact. Eleven survivors thrown out, one crawled through a fuselage gap	High impact. Survivors lucky
1-9-68	0	FATAL	Nose wheel collapsed. Some time later fire broke out in belly compartment	
4-8-68	5	127	Takeoff; engine fire-landing, engine fell out. Integrity of fuselage breached by an explosion-left wing fuel burning (Reference CAP 324)	Slow evacuation
4-20-68	123	129	Crashed after takeoff and burned; broke into four sections with wreakage widely scattered	High impact

4-28-68	0	3	Struck ditch; explosions involved; - destroyed	
6-13-68	6	63	Crashed on approach and burned (power plant fire); severe impact; collided with trees	Severe impact
6-24-69	0	FATAL	Destroyed on airport; severe impact and fire	
10-16-69	0	FATAL	Severe impact; collided with dirt bank; explosions and fire; aircraft destroyed	
4-18-70	0	FATAL	Engine failure and fire coming down runway caught up with one exit; firefighting equipment reached aircraft after flight deck and first class section flaming; gutted internally--sidewalls still standing but ceiling areas above racks, windows and doors eliminated	
11-27-70	47	229	Takeoff aborted; aircraft still moving when lefthand overwing exit opened and fire came in for a short time period; two fuselage breaks (aft section of cabin broke open and right wing tore loose spilling fuel); fire under left wing, large fire erupted on right side (explosion several minutes later); 6 to 8 inches of fuel in and around aircraft; large amount of raw fuel in aft cabin area; passengers attempted to move away; aircraft still impacting, therefore injuries; interior equipment loose	Severe impact

12-28-70	2	55	Bounced on landing; severe impact; wing fire and fuselage break	Severe impact
11-28-72	60	75	Engine fire on takeoff (?), banked and fell 400 feet--"ball of fire	
12-8-72	43	61	Landed on house	
12-20-72	10	45	Hit CV880 on takeoff; engine fire and smoke poured quickly into cabin	

NOTE: Data based in private communications, McDonald Douglas Corporation

25.803 requires that an airplane model having a seating capacity of more than 44 passengers must undergo an emergency evacuation demonstration under dark night conditions using one half of the available emergency exits and be completely evacuated of passengers and crew in 90 seconds. The passengers in this test must not be experineced in evacuation demonstrations and must be representative of the typical age/sex mix encountered in airline service. The crew and passengers have no prior knowledge as to which emergency exits have been rendered inoperative for the demonstration. The action of the cabin attendants in locating the operative exits and routing the passengers to these exits and out onto the escape slides is vital in meeting the 90-second maximum evacuation time. This demonstration is the "proof" test of the emergency evacuation provisions concerning exits and escape slides and crew procedures that make up the overall evacuation system.

Revised FAR 25 emergency evacuation and crashworthiness standards were adopted in 1972. They require that each stowage compartment in the cabin (except underseat and overhead passenger convenience compartments) be completely enclosed and that every item of mass in the cabin be restrained for crash landing conditions. Emergency overwing exits which were previously required by FAR 25.807 to be at least 19 by 26 inches were enlarged to 20 by 36 inches. The escape slide for each non-overwing exit more than 6 feet above the ground is now required by FAR 25.809 to have a quick acting one-motion automatic deployment/erection sequence actuated upon opening of the exit from inside the airplane (previously, separate deployment and erection motions were allowed). A new standard in FAR 25.809 requires that exits opened by a single power-operated system must be operable within 10 seconds after failure of the system with the aircraft in level attitude and with gear collapsed.

Standards in FAR 25.811 require that an exit sign be located above the aisle near each exit and beside each exit (previously above-aisle signs were required only for overwing exits and next-to-exit signs only for floor level exits) and that handle identification and cover removal instructions be self-illuminated for 20 by 36 inches exits. New standards in FAR 25.812 require that the emergency lighting power supply be independent of the main lighting power supply and allow sources of illumination which are common to both systems. Provisions pertaining to conspicuousness of emergency exit signs located above the aisle and next to exits and on bulkheads or dividers which obscure an exit from passenger vision were tightened. Standards also were upgraded for emergency illumination along the aisles and passageways leading to each floor-level emergency exit and for exterior emergency lighting for overwing escape routes and non-overwing exits. The access requirements in FAR 25.812 were tightened for 20 by 36 inches exits.

If certification with ditching provisions is requested, it must be shown under FAR 25.801 that the general characteristics of the airplane in a ditching would minimize the probability of immediate injury to the crew and passengers and the

impossibility of their escape. It also must be shown that the flotation time and trim of the airplane will allow the occupants to leave the airplane and enter life rafts. FAR 24.1415 requires that enough life rafts, together with survival equipment including an emergency locator transmitter in one raft, be provided to accommodate all occupants of the airplane in the event of loss of one raft of the largest rated capacity.

The fire protection requirements applicable to materials used in emergency provisions located in the cabin such as flotation devices used as part of aircraft seats, exits, and signs are discussed in Chapter 6. The material used in evacuation slides and flotation devices not used as part of aircraft seats must be flame resistant when tested horizontally (average burn rate not to exceed 4 inches/minute). The material also will be acceptable if it does not support combustion after the ignition flame is applied for 15 seconds or if the flame extinguishes itself and subseuqent burning without a flame does not extend into the undamaged area. Consideration is presently being given to upgrading these flammability requirements for evacuation slide material.

D.2.1.2. FAA Operational Requirements for Civil Aircraft

Requirements concerning emergency evacuation demonstrations by operators of transport aircraft and crew member emergency training are included in the following standards of Part 121 of the Federal Aviation Regulations:

FAR 121-291 – Demonstration of Emergency Evacuation Procedures

FAR 121-417 – Crew Member Emergency Training

If an airplane model is introduced into passenger-carrying operations by an operator whose crew procedures were not incorporated in the emergency evacuation demonstration conducted by the airplane manufacturer, FAR 121.291 requires the demonstration be repeated by the operator. The operator must also conduct an emergency evacuation demonstration if he increases the passenger seating capacity by more than 5 percent or incorporates a major change in the passenger cabin interior configuration that will effect the emergency evacuation of passengers. If the operator proposes to operate a land plane in extended overwater operations, he must also conduct a simulated ditching demonstration under daylight conditions using the airplane, a mockup, or a floating device simulating the passenger compartment. Each evacuee in this demonstration must don a life vest and enter a life raft which has been launched and inflated. All procedures in the operator's ditching manual are evaluated in this demonstration to assure that they are adequate and can be performed with reasonable effort.

D.2.1.3 Evacuation Systems Airplane Configurations

The new generation wide-body transports now in service (B-747, DC-10, L-1011) incorporate emergency provisions which comply with the upgraded FAR 25 standards adopted in 1972. The types of exits are as follows:

Type A – Floor level exit, 42 by 72 inches minimum

Type I – Floor level exit, 24 by 48 inches iminmum

Type II – Floor level or over-the-wing exit, 20 by 44 inches minimum

Type III – Over-the-wing exit, 20 by 36 inches minimum

The number of type of exits on each side of the cabin are based on the number of passenger seats according to the following table:

No. of seats	Type A	Type I	Type II	Type III
40-79	0	1	0	1
80-109	0	1	0	2
110-139	0	2	0	1
140-179	0	2	0	2
180-214	0	2	0	3
215-219	0	2	1	2
220-224	0	3	0	2
225-279	1	2	0	2

Over 299 seats, each emergency exit is either a Type A or Type 1. One hundred seats are allowed for each pair of Type A exits and 45 seats for each pair of Type I exits. If rate of egress is equivalent to a Type III exit with the airplane in the most adverse exit opening condition due to landing gear collapse, 12 additional seats are allowed for a central exit and 15 for a tail cone exit.

Evacuation chutes are provided for each emergency exit which is more than six feet from the ground with the landing gear extended. The chutes installed in accordance with the FAR 25 regulations adopted in 1972 are automatically deployed when the exit handle is actuated from inside the airplane.

D.2.1.4 Crew Procedures

FAA requirements cover minimum crew training. Experiments and actual accidents have demonstrated that proper action by cabin crew on commercial aircraft in an emergency is a major factor in passenger escape.[9] The crew must retain compusure and must be completely familiar with emergency procedures and facilities. In most accidents, the cabin crew are the only organized means of assistance available to the passengers.

Prior to takeoff, the cabin attendants brief the passengers on the location of emergency exits and the use of seat belts. Printed cards are provided for each passenger which supplement the oral briefing and contain diagrams showing methods of operating the emergency exits and other instructions necessary for use of emergency equipment.[19] In situations requiring an emergency evacuation, the flight crew and cabin attendants are trained to act promptly and to carry out an emergency evacuation on their own initiative and to recognize the necessity for the use of good judgment.[18] The cabin attendants are trained to recognize when evacu-

ation equipment is inoperative or faulty and to act promptly in preventing the use of such equipment and to quickly divert evacuating passengers to usable exits.

A schematic for crew emergency procedures is presented in Figure D-1.

Assuming passenger survival of the initial accident impact or other problem. the primary hazard requiring rapid evacuation of an aircraft is fire. With fire come the added dangers of explosion, toxic gases, and smoke. A major fuel fire outside an aircraft fuselage can melt the fuselage in less than a minute. Thus, it is mandatory that earliest evacuation be achieved where post-crash fire is involved.

Figure D-1- Schematic of Crew Emergency Procedures

IN-FLIGHT PREPARATION

Advise ATC & company of airplane condition & intent to evac.

Alert Flight attendants prior to passenger announcement

Determine pass load, No. of evac trained employees, infants, or others needing special considerations

Inform inflight supervisor of time available for prep. nature of emerg expected landing condition, brace signal to be used, any cockpit members to be in cabin for landing, & how cabin to be informed if evac not necessary

Direct nonessential cockpit members to assist in cabin prep.

Loose objects in cockpit, stow & secure

Secure COCKPIT DOOR open

EMER LIGHT sw on

Just before land, CABIN PRESS MAN/AUTO sel to manual

MAN CAB ALT cont to full open

If released from cockpit, S/O sits near DOOR 1L

Avoid landing until EMER EQUIP & CREW are ready

Advise passengers when to BRACE for landing

When airplane stopped, is EVAC reqd?

YES

NO

Notify CABIN accordingly

If preparations made, CABIN ATTENDANTS will EVAC passengers when A/C stops unless directed not to EVAC.

If evac started, shut down all engines

IMMEDIATE ACTION

Park. Brake to PARK

Speed Brake handle to retract

Flap Slat handles to POS 35

Evac Comd sw on

Eng Fire Handles all full down

Fire Agent disch as read

APU Master sw off

APU Fire Cont sw to APU Off/Agent Arm

Fuel levers off

If VHF Comm 1/PA reqd. Emer Pwr sw on

Just before leaving cockpit, Bat & Emer Pwr sws off

Take emergency transceiver

Continued

PREPARATION FOR PASSENGER EVACUATION (CABIN ATTENDANTS)

If MINIMUM TIME FOR PREPARATION

SHOUT – GRAB ANKLES, KEEP YOUR HEAD DOWN UNTIL AIRPLANE STOPS

IF TIME PERMITS

At night, turn CABIN LIGHTS full bright

Reseat passengers as required. Clear seats for helper passengers

Using SAFETY CARD, instruct passengers on protective position, seat belts tight, & brace signal

Tell passengers where, when, & how to evacuate

Brief HELPER passengers

Open CURTAINS

Latch INTERNAL DOORS open

IMMEDIATE ACTION

Remove SHARP OBJECTS including HEELS

Stow all loose objects

Clear seat at DOOR 1L for S/O if rel from cockpit

Advise CAPT of completed procedures

SEAT BACKS in proper position

Assure SEAT BELTS tight

Sit in assigned seat for landing

SIGNAL TO BRACE

Continued

APPENDIX D

IMMEDIATE ACTION Crew Duties

CAPTAIN

Immediately following cockpit shutdown, proceed to the main cabin and direct and assist evacuating passenger as conditions indicate. When all possible assistance has been rendered, leave the airplane, administer first aid as appropriate, assemble passengers away from the airplane and provide for passenger comfort.

FIRST OFFICER

Immediately following cockpit shutdown, proceed to the main cabin and ensure proper exit operation of all doors on the *right* side of the cabin by proceeding successively from door #1 through door #4. At any unusable door, redirect passengers to the nearest operating exit. When all possible assistance has been rendered, leave the airplane. When outside, administer first aid as appropriate, assemble passengers away from the airplane and provide for passenger comfort.

SECOND OFFICER

Immediately following cockpit shutdown, proceed to the main cabin and ensure proper exit operation of all doors on the *left* side of the cabin by proceeding successively from door #1 through door #4. At any unusable exit, redirect passengers to the nearest operating exit. When all possible assistance has been rendered, leave the airplane. When outside, administer first aid as appropriate, assemble passengers away from the airplane and provide for passenger comfort.

END

Cabin fires of high intensity also require earliest evacuation from a heat and toxicity standpoint.[14]

Airline cabin attendants give passenger briefings on safety and evacuation items prior to departure; however, the comprehension of this information by the passengers appears low.[18, 19] In an emergency evacuation, passengers tend to head toward the entrance they used in boarding. Design of emergency evacuation systems must be based on low expectation of passenger competence in an evacuation. Particular consideration should be given to the simplest possible devices for operating evacuation systems. Proper passenger briefing may minimize panic in an emergency.

In the event of an accident, the crew must give passengers notification as to when and where to evacuate.[1] Some passengers appear stunned in accidents and may remain in their seats unless prodded to move. Proper marking of emergency exits is mandatory to prevent confusion. Power and lights may be missing following an accident; thus, self-contained evacuation announcement systems must be considered for large aircraft.

Speed of evacuation indicates that injured or infirm passengers be handled so as not to impede the evacuation of others; young children present special problems in communicating and behavioral patterns. This problem must be considered in the design of exits and in crew training. Of equal importance, infirm and child passengers should not be seated at exits which are passenger-operated during an emergency.

D.2.1.5 Human Factors

Human factor aspects of design and operations of aircraft evacuation concepts and systems must be considered.[10,11] The aircraft designer can expect a trained crew; however, evacuation systems should be designed for easy and natural use by crew and passengers.[2,12]

Aircraft must be designed and loaded so that if an accident occurs, a minimum of debris is scattered around the cabin to impede the evacuation. Particular care must be paid to galley equipment and passenger hand luggage. Sharp edges of torn metal and broken seats are further impediments to evacuation.

Emergency exit location, accessibility, and size are extremely important for emergency evacuation.[5] Particular attention must be paid to the size of the exit and to the technique of operation for emergency exits where power is not available and the structure is deformed (as in a crash).[8,17]

Loading platforms, stairs, inflatable slides,[25] and ropes comprise the normal evacuation devices from an airplane.[23] Simplicity and reliability of self-contained devices on the aircraft are mandatory.[4] Experience has shown that assistance of trained crews are necessary to minimize a pile-up problem at the bottom of an evacuation device.[3] This problem also exists in situations wherein passengers jump on top of each other or into life rafts. Few, if any, passengers have ever participated in an emergency evacuation of an aircraft. Thus, the entire evacuation system and its devices must consider all passengers as untrained.[6,24]

Following an accident, there will be probably no light at night. Even during the day, vision may be obscured by smoke. Emergency lighting, special identification of emergency exits, acoustic or tactual guidance, or other concepts for assisting passengers to leave the aircraft should be provided.

D.2.2 Military Aircraft – Egress Time and Difficulty

The requirement for minimum time to escape from military transports (C-5, C-9, C-141, C-130, C-118, etc.) have been defined in the following documents:

AFSC DH 1-6 – System Safety Design Handbook

AFSCM 80-1 – Handbook of Aircraft Designers

Mil-Std-872 (USAF) – Test Requirements and Procedures for
Aircraft Emergency Ground and Ditching Escape Provisions

These documents require that egress be accomplished in 60 seconds maximum, with

one half of the exits blocked. Specific times for emergency egress from operational combat and training aircraft are specifically so detailed with each system having specific egress routes and times.

The ability to egress from military aircraft must be defined by the type of aircraft involved. For transport type aircraft egress patterns and techniques follow somewhat those of the commercial version of the same type of aircraft. (Transport crews are generally not provided parachutes.) In bomber aircraft egress becomes more complex in that clear routes of escape are more difficult to establish and in most cases each crewman has an ejection system which has an "on the ground" ejection escape and survival capability. Fighter aircraft are similar to the bomber except the main means of escape on the ground is either ejection or over the side of the cockpit. Helicopters provide relatively simple egress routes, however the threat of fuel spillage and fire is very critical and escape is heavily dependent on the type of accident.

Military transport aircraft fall into two categories. These are combat operational transports and personnel transports (including Command and VIP persons). The latter fall in the same category as the commercial versions of the same aircraft. Combat operational transports differ in that the interiors contain little more than seats (sometimes metal) and typical thermal-acoustical insulation with a fabric outer shell. In addition to the passengers this type transport could be carrying cargo in the form of vehicles, weapons, etc., all of which would propagate fire in case of an accident. Serious efforts are being made to develop "blow out" panels in the passenger areas that would be activated by the flight crew to provide many egress points. Until this new technique is developed and incorporated into transport systems, escape will be limited to cargo and jump (for parachute troops) doors located primarily at the side and rear of the aircraft. The reduced volume of flammables in the passenger compartment reduces the tendency for rapid smoke and toxic gas buildup, however the presence of fuel (in vehicles) and munitions could increase the fire and heat potential, thus reducing the chances for safe egress.

The emergency egress systems vary within specific types of combat operational transports. In most cases the flight deck personnel escape using ropes which are thrown out of the forward crew door. In most aircraft the passengers use escape slides to egress from the aircraft. However, the C-141 and C-130 transport cargo doors are close enough to the ground to allow escape by climbing down rope ladders or jumping. In Figure D-2 the emergency exit doors on the C-141 are shown, and the proximity to the ground (less than 6 feet) is apparent. During a series of ground evacuation tests using the C-141, it was found that the average time required for 140 paratroopers to get out of the aircraft was 243 seconds. Compared to the requirement of 60 seconds for escape the time seems unusually long. The utilization of the C-5 in airlift operations brought about the need for more detailed evacuation tests because of the size of this aircraft, its having two decks or levels and the large passenger carrying potential. This aircraft utilizes escape slides, ladders, etc., depending on where the exit is located and what personnel are using the

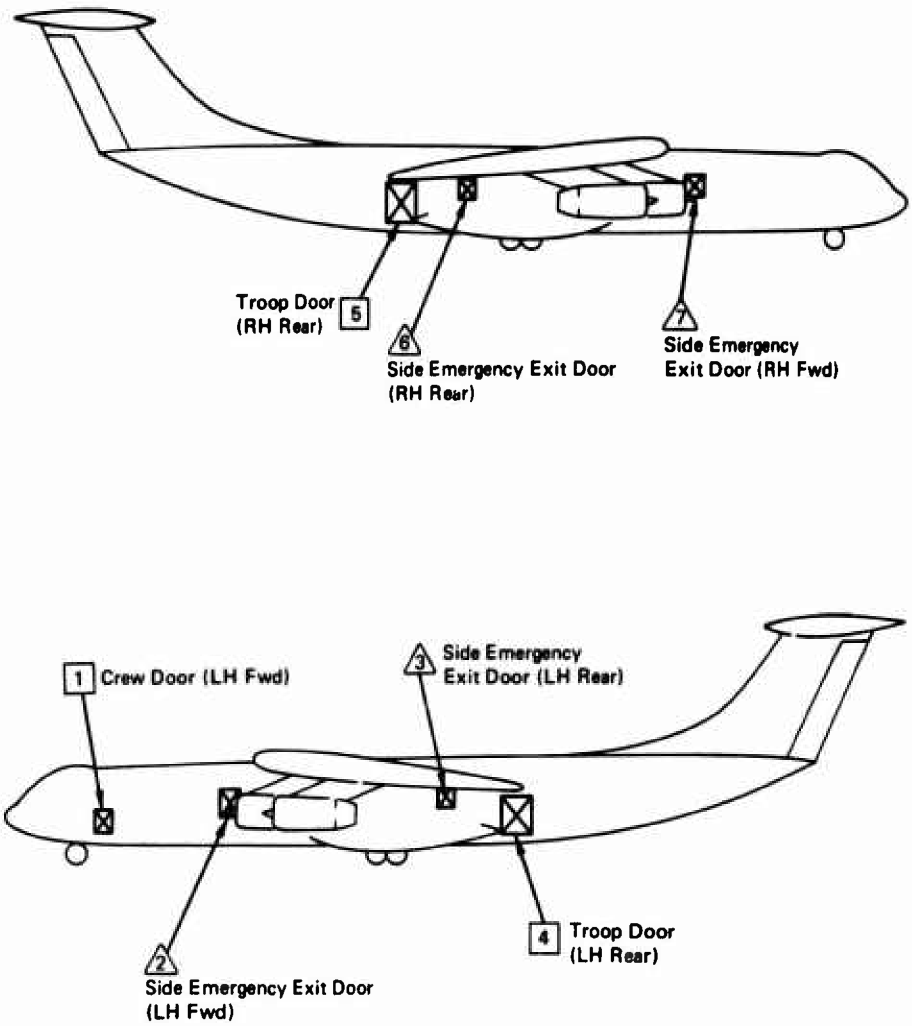


Figure D-2 C-141A Ground Exits

exit. The multitude of exits are shown in Figure D-3. The cargo compartment is the lower level. In a series of tests conducted to evaluate the escape systems personnel were evacuated from both upper and lower levels simultaneously. An operational C-5 was utilized in these tests.

Review of military aircraft accident records confirm that egress from transport type aircraft is most difficult, primarily because of the number of personnel involved and their lack of experience in using the escape routes. Future efforts will have to be directed, as in commercial aircraft, in improving not only egress tech-

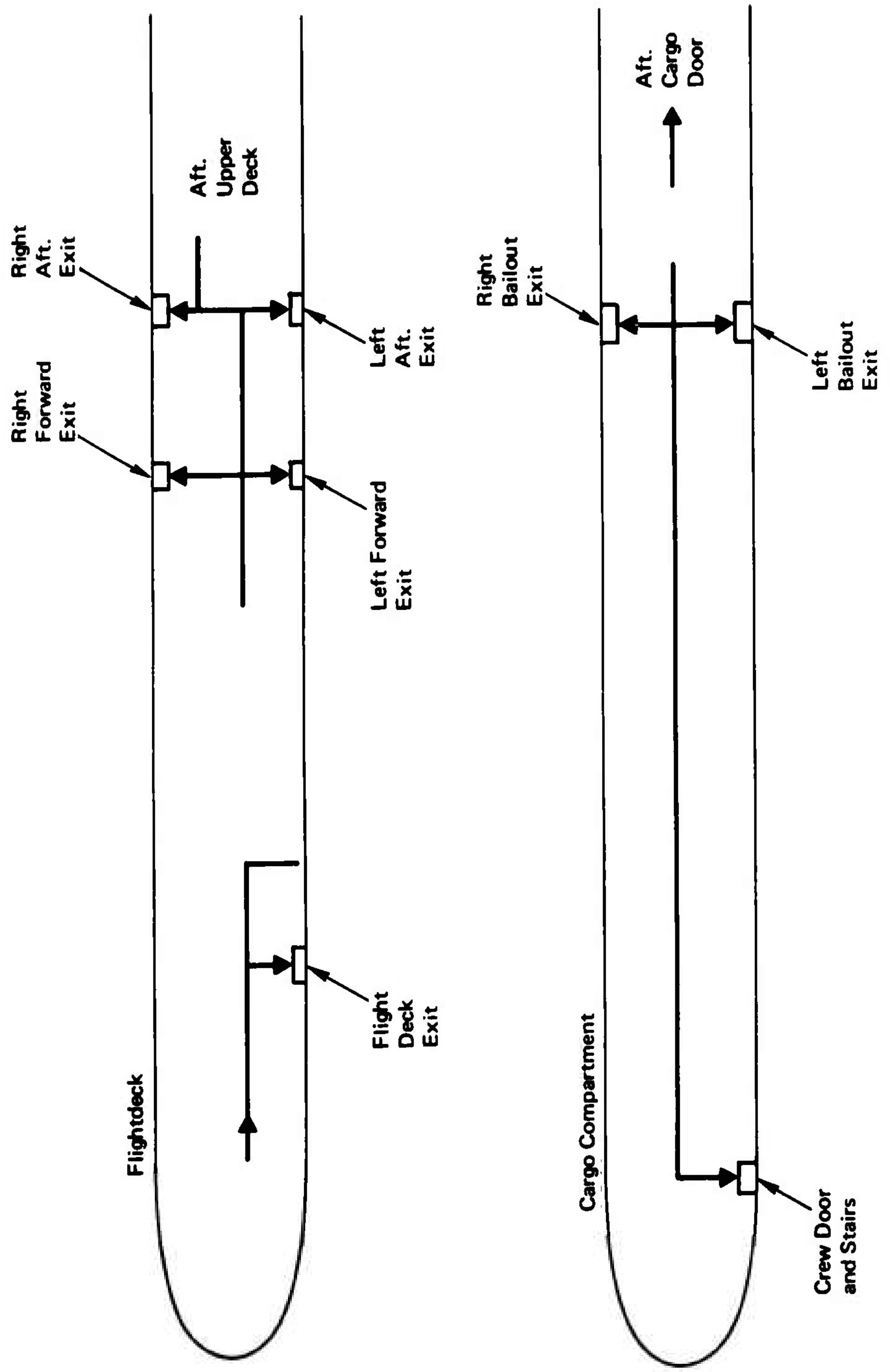


Figure D-3 C-5A Escape Exit Locations

niques, but in also making personnel knowledgeable in utilizing these routes under duress.

Radar picket type aircraft present a separate problem in case of fire and crash. This type of aircraft carries a large amount of electronic gear (which continually generates a large heat load), and the interior is fitted in a somewhat similar manner to a commercial transport since time of mission can exceed 24 hours. The high heat load from the electronic gear must be considered time to egress when a fire occurs. The use of large quantities of carpeting, upholstery fabric, bunk covers, etc., provides as in the commercial aircraft, the potential of yielding excessive quantities of smoke and toxic gases. Escape slides are provided ithese aircraft.

In bomber, fighter, and helicopter-type vehicles times for egress and escape from a burning aircraft must be accomplished rapidly (less than 10 seconds). This is dependent on the condition of the aircraft and occupants when the aircraft comes to a stop (if ejection has not been used). Damage to the aircraft structure would result in additional problems to safe and rapid egress of trapped airmen, reducing their chances of escape.

A survey of army helicopter accidents from January 1967 through December 1969, revealed the post-crash fires occurred in 9 percent of the light observation helicopter (LOH) accidents, 33 percent of the utility helicopter (UH) accidents, and 82 percent of the cargo helicopter (CH) accidents, and that the largest fatality cause in survivable CH accidents was burns due to post-crash fire (3 of 4 fatalities).[15] In April 1970, the first helicopter (UH-1H) to be equipped with a crashworthy fuel system (CWFS) rolled off the production line. In the ensuing 53 months, the Army experineced 838 accidents with CWFS equipped helicopters in operations including service in Southeast Asia without a single thermal fatality or injury.[13]

Only 21 post-crash fires occurred in those accidents of helicopters equipped with CWFS (one fire in 40 accidents) as opposed to 75 post-crash fires in 989 accidents of helicopters without CWFS (one fire in 13 accidents). The post-crash fires in the CWFS helicopters were small localized fires where flame propagation was delayed significantly to allow the occupants to escape or be rescued.

The significant reduction in post-crash fire fatalities indicates that similar analyses of commercial aircraft should be undertaken. Following such analyses, trade-off and desirable modifications could be accomplished.

D.3 Oxygen Systems

D.3.1 Flight Compartment Oxygen System

An independent oxygen system is available for crew members in the flight compartment. The system is a pressurized breathing pressure-demand type, intended for supplemental and protective breathing. Oxygen masks are installed on quick-release supports or hangers at each crew member's station in the flight compartment. Smoke goggles are also provided crew members in an enclosure adjacent to each crew station.

D.3.2 Passenger Compartment Oxygen System

An oxygen system is provided in the passenger compartment to supply emergency oxygen to the passengers and cabin attendants in the event of cabin depressurization. Records of U.S. airline depressurization incidents in 1970 reveal that 17 emergency descents were instituted and that oxygen masks were deployed in 13 of these incidents. McFarland[21] reported that 36 emergency descents occurred between 1959 and 1964 due to cabin pressure malfunctions in U.S. jet transports and that 59 occurred between 1965 and 1967. Cabin pressure malfunctions were usually caused by failure in the cabin pressure control system or compressor, windshield failure, open doors or hatches, or leaking door seals.

Emergency oxygen systems contain 10 percent extra masks and oxygen supply distributed uniformly throughout the cabin to provide for children in arms and stewardesses away from their stations. The oxygen masks contain three valves; (1) an oxygen inlet valve, (2) an exhaust valve, and (3) and ambient air inlet valve.

The relative proportions of oxygen and ambient air is a function of airplane cabin altitude. Some limited amount of mixing control can be maintained by the individual by varying his personal breathing flow rate.

Emergency oxygen systems in the B-747 wide-body jet transport and all narrow-body jet transports use gaseous oxygen stored in pressurized cylinders at 2000 psi pressure. These high pressure oxygen systems have been replaced in military C-5A and commercial DC-10 and L-1011 aircraft with self-contained modular type systems supplied from independent sodium chlorate type chemical oxygen generators.*[16]

Solid chemicals have been used as a source of breathing oxygen for more than 45 years. Sodium chlorate briquets were first used in the 1920s to supply breathing oxygen for mine rescue equipment. During World War II, prototype generators for aircraft were made and produced acceptable oxygen purity levels toward the end of the war. Development was pursued in the United States after the war and in 1958, the U.S. Navy started using chlorate generators in submarines for emergency oxygen. Studies initiated in 1967 resulted in the decision to use chemical generators as one source of oxygen for transport aircraft.

The chemical generator produces oxygen fro thermal decomposition of sodium chlorate. Sodium chlorate, along with a fuel and binder, is mixed and pressed into a cylindrical shape or core. By varying the composition and shape of the core, the desired oxygen flow rate is obtained. Burning is initiated at one end of the core by activating either a mechanical percussion device or an electric squib and continues progressively until the core is expended. The uninsulated generator housing surface can attain a temperature as high as 500°F (260°C) which occurs briefly during the first few minutes after ignition. A typical generator supplies an oxygen mass flow to each occupant for 15 minutes which is more than sufficient to meet

*also known as oxygen or chlorate candles.

mean tracheal oxygen partial pressure requirements prescribed in FAR 25. 1143. Once initiated, there are no means to extinguish the sodium chlorate core.

The DC-10 uses manually initiated generators which are located with masks in seatback compartments, in each lavatory, at each cabin attendants station, and in the lower galleys. When the cabin altitude reaches 14,150 + 350 feet, an aneroid transmits an electrical signal to an electro-mechanical device which opens the seatback compartment door, exposing one, two, or three oxygen masks, depending upon the seat location. The passenger, in pulling the mask to his face, pulls a lanyard that removes a pin from the generator initiating flow of oxygen. If only one mask in a two or three mask group is pulled,pxygen will also flow to the mask(s) remaining on the compartment door. It has been calculated that the oxygen concentration in the cabin will increase from 20 to 23 percent with oxygen flowing to all masks for 15 minutes at sea level with no ventilation. The increase is less with cabin ventilation.

The L-1011 uses electrically initiated generators which are located in the overhead service compartment at the seat station. A central control unit automatically activates all generators and drops all oxygen masks when the cabin altitude reaches 13,000 feet. Oxygen will be flowing to the passenger by the time the mask is donned. Oxygen will also flow to masks that are not used.

The DC-10 and L-1011 chemical oxygen systems have been certified to be in compliance with the oxygen equipment fire protection requirements of FAR 25.1451 in that no oxygen equipment is installed in or near any designated fire zones. However, no assurance is given relative to fires adjacent to the oxygen equipment. The equipment is installed so that escaping oxygen cannot cause ignition of grease, fluid, or vapor accumulations that are present in normal operation or as a result of failure or malfunction of any system. The generators have been qualified in a gasoline vapor explosion test with no problem. They have also been tested in a representative crash-fire environment.

Compared to the high-pressure gaseous oxygen system, the use of chemical oxygen generators eliminates interconnecting pluming and latch valve manifolds at each seat group. Lack of high pressure in the generator system is a safety advantage and there is no need for periodic hydrostatic testing or topping off. Chemical generators can be easily stocked and have a useful life of 10 years. Their use also result in simplified logistics requirements since high pressure oxygen servicing equipment is not needed for the passenger compartment oxygen.

There is little question that the sodium chlorate oxygen generating system has substantially reduced the hazards and costs of *servicing* oxygen systems on aircraft (as compared to a bottled-pipe pressurized oxygen system). However, there are other problems and elsewhere in this appendix there are discussions and recommendations relating to provision of a modified life support system for passengers.

D.3.3 Portable Oxygen — Flight Compartment

A high pressure 11 cubic foot portable gaseous oxygen-cylinder is installed in

the flight compartment for use by the crew. The cylinder is mounted with quick detachable provisions and is equipped with a smoke mask.

D.3.4 Portable Oxygen – Cabin Attendants

Eight 4.25 cubic foot high pressure gaseous portable oxygen cylinders for use by cabin attendants are provided. Six cylinders are mounted with quick detachable provisions in the main cabin with two similarly mounted located in the lower galley if the aircraft is so configured. All cylinders are equipped with oxygen masks.

D.3.5 First Aid Oxygen

One 4.25 cubic foot high-pressure portable oxygen cylinder per 50 passengers is provided for dispensing first aid oxygen. The cylinders are mounted on quick detachable brackets and are equipped with oxygen masks.

D.3.6 Ventilating Systems and Pressurization

Ventilation systems, in use, vary in aircraft depending on manufacturer, re-fit status, etc. Some systems are once-through, others use varying recirculation and make-up air portions; most jet transports bleed heated air from the engine and subsequently mix it with air from ventilation intake.

These systems are designed primarily for passenger comfort in the non-emergency mode; in some cases, due to airflow and distribution, operation of the system during a fire could contribute to fire growth. Where cabin air is recirculated, operation of the system during a fire could serve to distribute smoke and toxic gases throughout the cabin. Further, since the passenger emergency oxygen system is not designed to protect against smoke inhalation and it mixes cabin air with the oxygen, passengers using the oxygen masks would normally receive a mixture of oxygen and cabin air including the smoke and toxic gases. Also it appears that certain ventilation systems utilize insulating or duct materials that are unnecessarily fire prone. In some cases the major distribution plenum, so insulated, runs the entire length of the passenger cabin overhead – the area most likely in a fire situation, to be heavily involved in heat, smoke and toxic gases and a potential flashover.

Thus, it appears that it would be desirable to review and analyze the fire characteristics and probable performance of existing aircraft ventilation systems and materials utilizing the fire scenario approach discussed in Chapter 3. The committee believes that such analyses could result in substantial changes to ventilation systems and materials used therein. It is also probable that the need for a carry-around (portable) life-support system for passengers will be highlighted; earlier FAA-sponsored passenger protection hoods could be further developed against this need.

D.4 New Conceptual Developments

Improvements in fire safety of materials, construction techniques, materials usage concepts, and aircraft operations are a continually evolving part of aviation.

The remainder of this appendix will cover some of the concepts to improve fire safety now under study. (Materials development *per se* will be covered in another part of this project.)

Programs for prevention of engine/fuel systems fires, electrical fires, and post-crash fires are emphasized in the following pages. It is recognized that fuselage usage of polymeric materials is the principal thrust of this report. The other systems which could ignite the polymers are touched on here to amplify the data given earlier in fire scenarios (Chapter 3).

It appears, that the problems of polymeric materials applications in military aircraft are similar to those in commercial aircraft. There is, of course, a substantial difference in priorities of applications and cost-effectiveness considerations.

D.4.1 Engine and Fuel Systems

D.4.1.1 Suppressions Systems

Engine nacelle fire suppression systems are generally installed on all multi-engine aircraft. Combustibles that must be considered include fuel, lubricating oil, and hydraulic fluid. Fire extinguishing agents utilized for this application are of the halogenated hydrocarbon type because of their greater fire suppression effectiveness compared to carbon dioxide. In addition, their more favorable physical properties, such as density and vapor pressure enable all overall reduced system weight. Specific halogenated hydrocarbon agents currently utilized for this application in the United States are bromochloromethane (CH_2BrC1)-Halon (1011), dibromodifluoromethane (CF_2Br_2)-Halon (1202), and bromotrifluoromethane (CF_3Br)-Halon (1301). In Europe greater use is being made of bromochlorodifluoromethane (CF_2BrC1)-Halon (1211). For high environment temperature applications (+450°F), 1, 2 dibromotetrafluoromethane-Halon (2402) is highly attractive. The quantity of agent necessary for effective fire extinguishment for aircraft engine applications is influenced, for example, by nacelle shape and roughness factors, air velocity, and rapidity and distribution of agent upon discharge. In general, available engine total flooding fire suppression systems provide for effective fire control in less than 2 seconds after system activation.

D.4.1.2 Jet Fuels

Aviation jet fuels currently utilized for military and commercial applications can be categorized in to two basic types — Jet B (Air Force JP-4) and Jet A or Jet A-1 (includes JP-8 and JP-5) — and are often referred to as high-volatility and low-volatility fuel, respectively. The relative fire safety of various jet fuels, particularly under aircraft crash environment conditions has been the subject of a long-standing controversy. A recent Air Force study concluded that: "At conditions encountered during most aircraft ground and flight operations, low volatility fuels such as JP-8 are in general safer than high volatility fuels such as JP-4." Since about 15 percent of the commercial operations involve high volatility fuels, the effect of fuel type on the safety of commercial aircraft is being reassessed.

D.4.1.3 Explosion Suppression by Ullage Fuel Enrichment

Hydrocarbon fuel-air mixtures exhibit a specific concentration range within which combustion is possible. These concentration limits are referred to as "the lean and rich" flammability limits. However, these limits cannot be relied upon to provide an adequate protection against ullage explosions. For high volatility fuels, such as JP-4, the fuel ullage can be made non-flammable by spraying fuel into the ullage.

It has been determined in past efforts, however, that the fuel spray must be heated to have an effective protection effect over the entire set of mission conditions. Although the approach is not currently utilized on aircraft for explosion protection, a heated fuel fogging development effort is currently under way in the U.S. Air Force to establish the practical utility of this method. From an analytical standpoint, the method potentially offers the lowest weight penalty of any of the suppression methods presently available.

D.4.1.4 Protection External to the Fuel Tank

Utilization of any of the fuel tank ullage explosions protection methods does not protect against external fires resulting from incendiary projectile hits into the liquid fuel phase. Certain protection techniques such as use of chemical extinguishing agents and inerting could also be utilized external to fuel tanks to counteract this fire hazard, if practical, from a particular configuration standpoint. Other approaches might include the use of flame retardant external void filler materials and self-sealing fuel tanks to limit the duration of fuel leakage and consequently the duration and severity of external fuel fires.

D.4.1.5 Modified Fuels

When commercial liquid fuel is released from a ruptured fuel tank under the dynamic conditions which occur in an otherwise survivable crash, much of the fuel is dispersed and vaporized in a mist of combustible fuel that may fill the aircraft. Any of the myriad of ignition sources normally available during an aircraft crash can ignite this mist and produce an intense fireball that could lead to destruction of the aircraft and its occupants. Programs are under way in the United States and in the United Kingdom to determine the fire reduction effectiveness of polymeric fuel additives that alter the misting characteristics of the fuel under crash conditions. These additives, when mixed (by 0.3 to 0.5 percent by weight in a low volatile fuel such as Jet A) tend to change the viscoelastic characteristics of the fuel so that it produces large droplets instead of a mist under crash conditions. The large droplets are harder to ignite and are less likely to allow flame propagation through the spray. Testing is currently in progress to establish the interrelationship between fire reduction effectiveness and additive-type concentration, fuel condition, fuel temperature, fuel quality, crash severity, and nature of ignition sources, in order to define the modified fuel behavior in a survivable crash. Tests to date do show safety

advantages of the modified fuels; however, many fuel systems are not compatible with modified fuels and further work on the concept is required.

D.4.1.6 Detection Techniques

Fire and overheat detection systems used in the engine nacelle of present day operational USAF aircraft have a poor reliability and performance record, evidenced by the number of false fire warnings and missed fires. Between 1965 and June 1973, over 80 percent of the reported fire alarms in USAF aircraft were false. In addition to being the cause of aborted missions and added maintenance, false fire warnings in USAF aircraft may have serious consequences in terms of damaged or destroyed aircraft and crew facilities. The detection system also failed to provide an alarm in 52 percent of the accidents/incidents involving aircraft engine necelle fires. It is almost impossible to assess the damage resulting from the system not providing the alarm. However, six accidents were noted wherein it appears that aircraft were either destroyed or received major damage as a result of the detection system not providing an alarm.

A variety of programs are under way under military, NASA, FAA and industrial sponsorship, to develop reliable fire detection systems. These developments include new sensor concepts and specific programs to protect current systems and minimize false alarms. Some details on these programs are included in Appendix C.

D.4.1.7 Liquid Nitrogen Fuel Tank Inerting

Nitrogen is used to dilute the air within the fuel tank ullage to the point where the oxygen concentration is insufficient to support significant combustion overpressure. This is accomplished by cryogenic nitrogen on the aircraft in dewars and providing the nitrogen to the fuel tank through the vent system. A concentration level of 9 percent oxygen by volume is considered the maximum "safe" oxygen concentration for most aircraft applications. This technique has been flight tested by USAF on C-135, C-141 and by FAA on DC-9 aircraft and is presently being installed in the C-5A fleet. Nitrogen inerting systems for fuel tanks are also being designed for supersonic military aircraft (B-1).

Ramp fires for unattended aircraft could be eliminated or reduced by using inert gases (nitrogen) to reduce the oxygen content inside the aircraft below 10%. Although two advanced techniques are being developed to provide on-board generation of the inerting gas, they are not yet ready for practical implementation.[20,22]

D.4.2 Passenger Protection

D.4.2.1 Emergency Evacuation

Developmental efforts are in progress by the FAA to study emergency evacuation problems and improve emergency evacuation provisions. In one project, a variable position cabin mock-up was used to study the effects of cabin tilt and pitch on the ability of the passengers to evacuate an airplane which has come to rest in an unlevel attitude. These tests were conducted with single-deck and double-deck

cabin configurations. Evacuation tests were also conducted using a mock-up SST cabin incorporating Type A, Type I, and Type III exits (see paragraph D.2.1.3). These tests indicated that the Type A exit where two passengers can evacuate simultaneously result in a higher evacuation rate by a factor of two compared to the Type I or Type III exits. An emergency evacuation mathematical model is presently being developed by the FAA to investigate the influence of disabled passengers and other variables, such as obstacles, damage, and fire on the evacuation process.

D.4.2.2 Oxygen Mask Systems

The FAA is investigating the use of improved oxygen mask systems for commercial aircraft. A new type of mask, that re-circulates the unused oxygen exhaled by a passenger and does not mix with cabin air, is being considered. This mask would filter out carbon dioxide exhaled by the passenger. This mask would be detachable from the aircraft and would incorporate a storage bag containing enough oxygen to sustain life for several minutes during evacuation. The principle underlying this concept is the reutilization of the 93 percent of inhaled oxygen which is exhaled by a person in normal breathing. Furthermore, available filtering devices offer the possibility of removal of most of the toxic gases produced in aircraft fires. This allows consideration of use of materials that do not produce any toxic combustion products.

D.4.2.3 Improved Means of Egress

The FAA studied the feasibility of using a liquid explosive linear-shaped charge to open jammed exits and to open predetermined new areas for mass evacuation. This linear-shaped charge system used nitromethane and a sensitizer which are stored separately and mixed to form an explosive charge when the exit is activated. Upon activation, the liquids are pumped into a tube outlining the area to be opened and detonated, creating a localized explosive action that cuts open the fuselage skin. The U.S. Air Force is evaluating the solid linear-shaped charge concept and has modified an exit on a C-131B airplane to determine its reliability after a flight endurance test program. Determinations will be made regarding the maintenance requirements, capability of the system to perform following prolonged standby time, and whether any hazard exits to flight safety.

D.4.2.4 Water-Fog Systems

A fire protection concept that has been tested with limited success, but not yet incorporated in aircraft designs, is the water-fog fire suppression system. It would be similar to a sprinkler system for fire control in buildings. An aircraft system might make use of potable water and collected waste water from lavatory and galley basins that would be pumped to nozzles in the passenger cabin. The water-fog would be discharged into a section of the cabin where fire was detected and would wet all accessible surfaces while spraying a cooling fog into the cabin air.

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APPENDIX E

QUESTIONAIRE ON FIRE SAFETY ASPECTS

OF POLYMERIC MATERIALS

AIRCRAFT: CIVIL AND MILITARY

ORGANIZATION ____________________ INDIVIDUAL ____________________

____________________ DATE ____________________

APPLICATION Covering -- Arm Rest

USE INFORMATION

Use, location, amount, and aircraft(s)	Passenger seats -- B707 xx pound per plane

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POLYMERIC MATERIAL

Components, chemical, composition (polymer, plasticizer, filler, etc.), configuration, manufacturer's designation	Vinyl coated fabric -- polyvinyl chloride plasticized with 30% octyldiphenyl-phosphate coated on Nylon 6 fabric PVC — Diamond Shamrock — 450 Octyldiphenylphosphate — Monsanto — Santicizer 141 Nylon 6 — Allied

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BASIS FOR SELECTION *

Indicate priorities for selection (1 = highest) for each defined component in the application

Column A) Polyvinyl chloride
Column B) Phosphate plasticizer
Column C) Nylon fabric

	A	B	C
Fire Safety	3	1	
Structural requirements			1
Commercial availability			
Weight			
Manufacturability	2		
Aesthetics, decor			
Maintainability			
Cost	1	2	
Other (specify)			

FIRE RATIONALE

If fire rationale was consideration in choice of material, list flammability, smoke and/or toxicity tests used. *If fire was not considered, state none.*	Required in accordance with FAR 25 . . . . . using Test Method #. . . . .

IMPROVEMENTS NEEDED

List critical improvements needed in the material	Reduced smoke and HC1 evolution in fire situation.

ADDITIONAL COMMENTS

1) Overall general comments about the application.
*2) If there are more than three components, include additional information here.

APPENDIX F

SYNOPSIS OF THE PHYSIOLOGICAL HAZARD

OF SELECTED COMBUSTION PROEUCTS

TABLE F-1 TOLERANCE TO SELECTED COMBUSTION PRODUCTS

Combustion Products	Hazardous Levels for Times Indicated			
	Minutes	½ Hour	1-2 Hours	8 Hours
Heat (°F)	284	212	150	120
Oxygen (%)	6	11	14	15
Carbon Dioxide (ppm)	50,000	40,000	35,000	32,000
Carbon Monoxide (ppm)	3,000	1,600	800	100
Sulphur Dioxide (ppm)	400	150	50	8
Nitrogen Dioxide (ppm)	240	100	50	30
Hydrogen Chloride (ppm)	1,000	1,000	40	7
Hydrogen Cyanide (ppm)	200	100	50	2

NOTE: Data from Table 1 in C. H. Yuill, "Pysiological Effects of Products of Combustion," American Society of Safety Engineers Journal 19 (1974): 36-42. Author notes that table is substantially that set forth in A. J. Pryor and C. H. Uill, Mass Fire Life Hazard, OCD Work Unit 2537A Final report (San Antonio, Texas: Southwest Research Institute, 1968), and that there is considerable variation among investigators as to what level of a particular gas does constitute a life hazard.

TABLE F-2 TOXICOLOGY OF SOME HIGHLY TOXIC FIRE CASES--Concentration (ppm) 760 mm, 25 °C

Gas	LTV*	Dangerous 0.5 to 1 hr.	Fatal 0.5 to 1 hr.	Effects
CO	50	1,500-2,000 (1 hr.)	4,000	Combines with heoglobin in blood to form carbohemoglobin thereby prevening O_2 transport. CO is a chemical asphyxiant.
NO	n. a.	100-150	400-800	Forms nitrous and nitric acids in presence of O_2 and H_2O in respiratory tract. Nitrates form methemoglobin while the nitrates lead to edema of the lungs. The latter are more dangerous.
NO_2	5			
HCl	5	1,000-2,000 (dangerous for brief exposure)	4,350	Neutralizes tissue alkali in upper respiratory tract. Causes death due to edema or spasm of larynx and upper respiratory tract.
Cl_2	1	50 (short exposure)	1,000 (brief exposure)	Hydrolyzes to nascent O_2 and HCl in respiratory tract.
$COCl_2$	0.1	12.5	25 (0.5 hour)	Hydrolyzes to HCl and CO at bronchioles and alveoli of the lungs. Pulmonary edema and asphyxiation.
HF	3	50-250 (brief exposure)	--	Ulceration of mucous membranes, chemical pneumonia.
COF_2	n. a.	--	--	Hydrolyzes to HF and CO. Similar to $COCl_2$.
H_2S	10	400-700	800-1,000 (high concentrations instantly fatal)	Irritant; combines with alkalis in skin to form Na_2S; pulmonary edema at high concentrations. Asphyxiant; paralysis of respiratory center.

HCN	10	400-700	100-200	Protoplasmic poison. Combines with enzymes associated with cellular oxidation. Death occurs through asphyxiation.
NH_3	50	2,500-6,500 (0.5 hour)	5,000-1,000 rapidly fatal)	Pulmonary edema.

NOTE: Data from Table VI in J. P. Wagner, "Survey of Toxic Species Evolved in the Pyrolysis and Combustion of Polymers," Fire Research Abstracts and Reviews 14 (1972): 1-23 based on:

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* Lower threshhold value; time-weighted average concentrations for a 7 or 8-hour period.

APPENDIX G

REVIEW OF CO TOXICITY:

Excerpt from R. R. Montgomery, C.F. Reinhardt, and J. B. Terrill, "Comments on Fire Toxicity," paper presented at the Polymer Conference Series (Flammability of Materials Program) Salt Lake City, Utah, July 11, 1974.

Carbon Monoxide (CO): In poorly ventilated fires with limited O_2 combustion is incomplete and the end products are CO and other degradation products, water, and less heat. Overall, of all the gases generated in real fire situations, CO is acknowledged as the gas that produces the most deaths [21]. The general physiological effect of increasing atmospheric concentrations of this colorless, odorless gas is shown in Table III [20, 33, 34]. Physical exertion, age, health and smoking habits can all affect individual response. Table IV as given in the account of an exposure to an estimated 900–1000 ppm CO from a leaking exhaust pipe into an Anchorage Alaska, sports arena [35], shows the variety of symptoms and the variation in response that may occur.

CO, unlike most poisons, has no known lasting effects if secondary tissue damage from O_2 depletion does not develop [12, 34, 36]. CO readily displaces oxygen from hemoglobin and also interferes with delivery of O_2 to tissues and removal of CO_2 from blood. Irreversible tissue damage may develop if the brain is deprived of O_2 for more than 5–10 minutes. However, adequate O_2 may again displace CO as shown in the equilibrium:

$$HbCO + O_2 \rightleftharpoons HbO_2 + CO$$

(where Hb means hemoglobin)

We can correlate percent atmospheric CO and time of exposure with blood carboxyhemoglobin. Several reviews [12, 34] discuss this subject in detail and an exhaustive study of the kinetics of uptake and elimination of CO has recently appeared [37].

TABLE III. PHYSIOLOGICAL RESPONSE TO CO (20,33,34)

CO in Atm%	Response
0.01	Allowable exposure for several hours.
0.04 - 0.05	No appreciable effect after 1 hour.
0.06 - 0.07	Just appreciable effect after 1 hour.
0.1 - 0.12	Unpleasant after 1 hour (headache, nausea).
0.15 - 0.2	Dangerous when inhaled for 1 hour (incapacitation, collapse).
0.3	Estimated danger level for 1/2 hour.
0.4	Fatal when inhaled for less than 1 hour.
1	Fatal when inhaled for 1 minute.

TABLE IV. SYMPTOMS AND SIGNS OF CARBON MONOXIDE POISONING REPORTED BY 51 ILL PERSONS PRESENT IN THE SPORTS ARENA ON MARCH 20, 1969 (35)

Symptom	35 Broomball Players Percent	7 Hockey Players Percent	9 Adults Percent	51 Total Percent
Headache	91	57	100	88
Dizziness	77	43	11	61
Nausea	49	43	44	47
Tinnitus	43	14	0	31
Disorientation	31	14	0	24
Numbness of feet	26	29	11	24
Blurred vision	20	--	--	14
Numbness of hands	9	--	--	6
Vomiting	3	--	--	2
Loss of consciousness	3	--	---	2

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APPENDIX H

SMOKE HAZARDS AND MEASUREMENTS

OF SMOKE OPACITY:

Excerpt from J. R. Gaskill, "Smoke Hazards and Their Measurement; A Researcher's Viewpoint," *Journal of Fire and Flammability*, 4 (1973): 279–298

[Smoke is defined] as the airborne products evolved when a material decomposes by pyrolysis or combustion. Smoke may contain gases, liquid or solid particles, or any combination of these.

Table 3. Smoke Hazards in Unwanted Fires

	Property	Hazard	Measurable
1.	Opacity	Hinders Escape and Rescue	Yes
2.	Lachrymatory Irritant	Induces Panic	No Being Studied
3.	Toxicity (Direct)	Incapacitates Kills	No Being Studied
4.	Toxicity (Indirect)	Anoxia	No Being Studied
5.	Heat	Sears Resp. System	No Being Studied
6.	Synergism	Combined Effects	No Being Studied

SMOKE OPACITY

Smoke opacity, or light obscuration, is commonly measured by determining the attenuation of light from a source through a column of smoke onto a photoelectric cell. Table 4 shows the methods commonly used in this country for this purpose. The Steiner Tunnel (ASTM E-84), originally designed to measure the spread of flame across a ceiling surface, has been adapted to measure the obscuration of smoke as it passes through the exit flue. At the present time, this is the only smoke test commonly accepted. However, it has been subject to criticism both because of the location of the sample (some think that wall mounting or floor mounting would be preferable in some cases) and because it represents a limited set of fire parameters.

The XP2 Chamber (ASTM-D 2843) was developed and is used for measuring smoke density from burning plastics. It has been criticized both because of the small size of the sample involved and also the fact that it represents a single set of fire conditions. The NBS Chamber and the LLL modification both measure smoke density — light obscuration — by subjecting the sample to radiant heat (pyrolysis) or to radiant heat in the presence of a pilot flame (pyrolysis plus combustion). The LLL modification to date has consisted of adding a ventilation capability; and we are currently developing a higher radiant heat source. Both the NBS Chamber and the LLL modification have not presently been accepted as standard methods, but are used by a large number of laboratories throughout the country.

Table 4. Comparison of Smoke Test Systems for Measuring Smoke Obscuration

		Steiner Tunnel	XP2 Chamber	NBS Chamber	LRL Chamber
Sample:	Size	Large	Small	Small	Small
	Area (exposed	36 ft^2	1 $in.^2$ std (4 $in.^2$ possible)	6.6 $in.^2$	6.6 $in.^2$
	Thickness	Variable	~0.1–1 in.	0.002–1 in.	0.002 1 in.
Test duration (min)		10	4	<30 usually	>30 usually
Heat:	Source	Flame	Flame	Radiant + optional flame	Same as NBS
	Flexibility	±50%[a]	40 psi to 5 psi	+20%	800%
Ventilation:	Rate	240 linear ft/min	None	None[b]	Variable
	Flexibility	±35%	Possible	None[b]	0 to 20 changes/hr
Heat-transfer mode		Primarily convection	Convection/radiation	Radiation + some convection if flaming	Same as NBS
Smoke-production mode		Pyrolysis + combustion progressing along surface. Some penetration.	Combustion–total involvement to partial involvement.	Pyrolysis without flame; pyrolysis + combustion with flame—both on surface + penetration.	Same as NBS; higher heats may result in mostly combustion smokes.
Smoke measurement:					
Method		Integrated rate	Integrated rate	Accumulation; maximum rate is measured, as is obscuration time.	Same as NBS
Reporting		Area under obscuration vs time curve compared to that for red oak.	SDR (smoke density rating) in % of smoke obscuration-time curve.	Max density; max rate and time; obscuration time.	Same as NBS; material smoke obscuration index - sum of SOI's for various fire parameters.
Fire parameters possible		2	1	2	8
Equipment:	Cost	$40,000	$1000	$4000	$4500
	Portability	No	Yes	No	No
	Work space (ft)	20 x 30	3 x 5	(Movable)	(Movable)

[a]Not the standard method, but possible with the equipment.

[b]NBS has recently added a ventilation capability; the flexibility is thus ~800%.

LLL Approach

At Lawrence Livermore Laboratory we take the view that within the lifetime of a fire, the exposure of any material or material system of interest can be expressed by a series of bracketing parameters (see Figure 1); i.e., the material may be exposed to a low heat or a high heat or something in between. It may be exposed to flame or no flame. It may be subjected to no ventilation, to minor ventilation, or to considerable ventilation. The variable in the fire regimen is the kind, thickness, and attitude of the material.

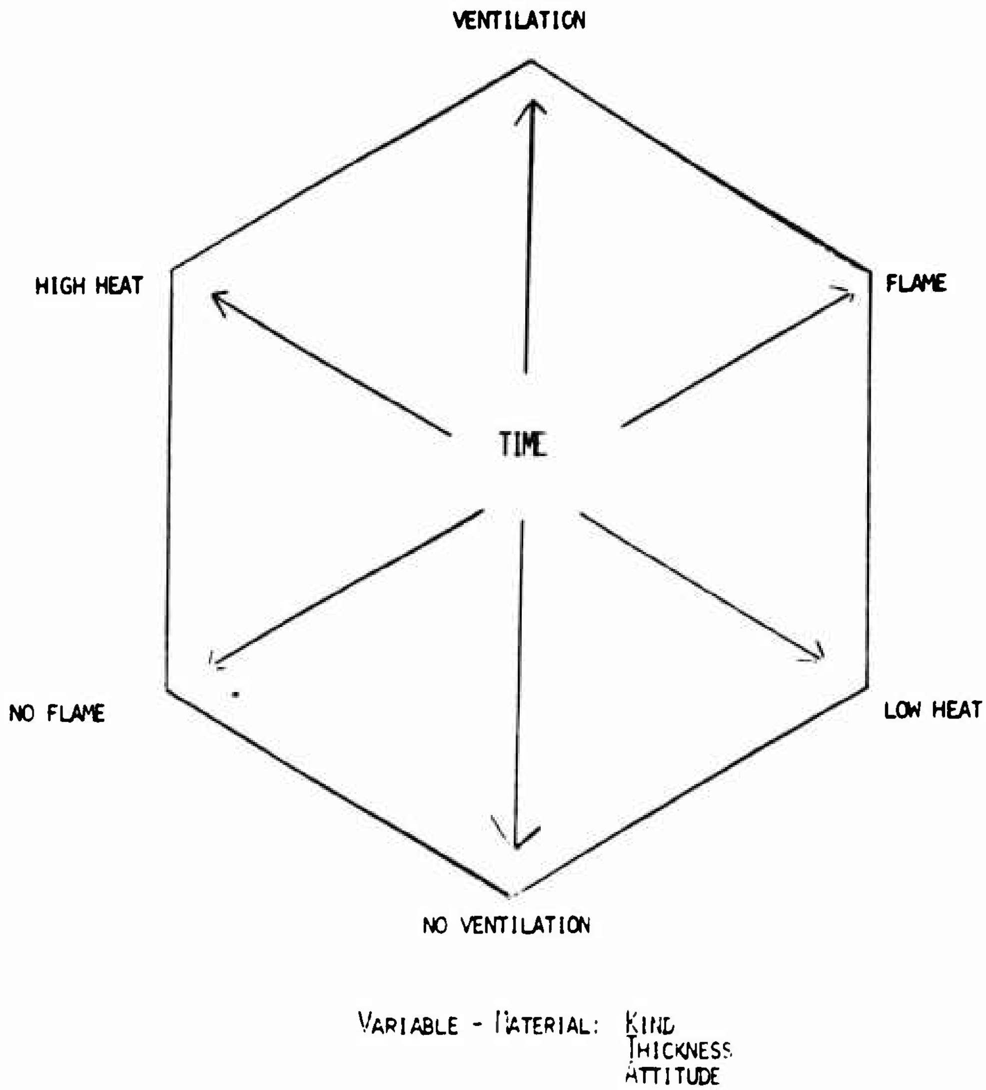


Figure 1 *Boundary conditions of a fire.*

APPENDIX H

We have exposed over 100 different material systems of limited thickness (up to one inch) and in one attitude (vertical) to what we term "low radiant heat" in the presence or absence of flame with no ventilation, or with ventilation rates up to 20 air changes in an hour. Our findings have been reported in the literature [7, 8]. However, a brief description of the methods used and some of the salient results may be of interest.

Figure 2 shows a picture of the LLL Density Chamber, which consists of an 18 cubic foot aluminum box, 3 feet high by 3 feet wide by 2 feet deep. A 3 by 3 inch-square sample of the material under test, mounted in a metal frame and held vertically, is slid in front of a radiant heat source operating so that the flux on the surface of the exposed specimen is 2.5 watts per square centimeter. As the sample pyrolyzes it generates smoke which rises and intercepts a vertical light beam located at the top of the chamber and focused onto a photoelectric cell in the bottom. The loss in light transmission is measured by a recorder operating through an amplification system. For the flaming exposure condition, a series of six small pilot flames are positioned at the bottom face of the sample about one-fourth of an inch away in order to ignite any flammable species emitted by the decomposing specimen. In tests where ventilation is a factor, air is admitted through a slot in a horizontal tube located in the lower right-hand edge of the chamber and is exhausted through a port located in the upper left-hand back corner of the chamber.

Table 5 shows the various data obtained in testing a material in our chamber, the calculated values used, and the LLL in-house smoke standards employed to rate the obscuration properties of smoke from various material. Of interest is D_s, the specific optical density of the smoke. The laws of physics define the optical density of a medium as the logarithm of the reciprocal of the light transmitted through the medium. That is to say, if the light transmitted through a medium is 10% of that incident upon it, the optical density is 1; if the light transmitted is 1%, the optical density is 10, etc. The specific optical density is a calculated value that reduces the area smoking, the volume involved, and the light path all to unity. In other words, it is the optical density that would be obtained if one square unit of material is evolving smoke into a volume of one cubic unit and the light is transmitted through a path of one linear unit. The utility of this specific optical density, D_s, will be discussed later.

Other values of interest are D_m, the maximum specific optical density obtained in a test; T_m, the time it occurs; R_m, the maximum rate of change of specific optical density; T_{rm}, the time at which it occurs; and T–16, the time at which the specific optical density reaches a value of 16. Tests by Shern [9] have indicated that masked observers found it difficult to see through smoke with a specific optical density of 16.

One additional value which we have found useful is the smoke obscuration index (SOI). This is defined by Gross and Robertson [9] as being proportional to the product of the maximum smoke density and its rate of rise and indirectly proportional to obscuration time; i.e., T–16. The mathematical derivation of the SOI is given in References 8 and 9 and is expressed as shown in Table 5.

Table 5. Key to Symbols Used and LLL Smoke Density Standards

Symbol	Definition
Ds	Specific Optical Density $= \frac{V}{AL} \left(\log_{10} \frac{100}{T}\right)$
V, A, L	Respectively, chamber volume, exposed sample area, and length of light path – all in consistent units. For the LLL Chamber V/AL = 132
T	Light transmission – percent
Dm	Maximum D_s attained in a test
Tm	Time to attain Dm – minutes
Rm	Maximum $d/dt(D_s)$ – minutes^{-1} (averaged over 2 min.)
Trm	Time at which Rm occurs – minutes
T-16	Time at which D_s = 16, in a test – minutes
SOI	Smoke Obscuration Index = DmR/T-16

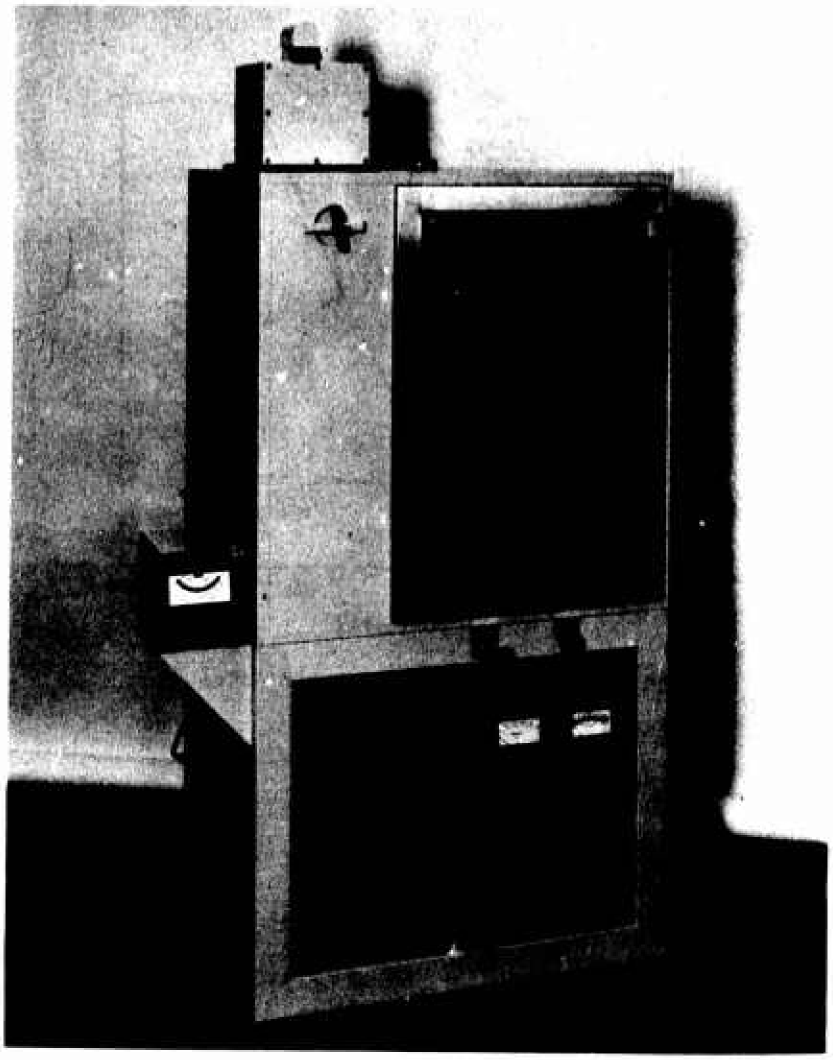
$$SOI = \frac{D^2m}{2000\ T\text{-}16}\left[\frac{1}{T_{0.9} - T_{0.7}} + \frac{1}{T_{0.7} - T_{0.5}} + \frac{1}{T_{0.5} - T_{0.3}} + \frac{1}{T_{0.3} - T_{0.1}}\right]$$

$T_{0.9}$, $T_{0.7}$, etc.	Time (min.) to reach 0.9 Dm, 0.7 Dm, etc., respectively

LLL Smoke Standards

Item	Values and Description			
Dm Maximum Smoke Density	<25 light smoke	25-50 moderately dense smoke	100-400 dense smoke	>400 very dense smoke
T-16 Visual Obscuration	>10 very slow smoker	10-5 slow smoker	5-1 moderately fast smoker	<1 very fast smoker
SOI Smoke Obscuration Index	0-5 safe smoke	5-10 probably safe smoke	10-30 probably hazardous smoke	>30 hazardous smoke

Also shown in Table 5 are the in-house smoke standards used at LLL to attach descriptive terms to values obtained for maximum smoke density, obscuration time, and smoke obscuration index. These values, their segregation, and their



terminology have been based on our experience in the field, plus consultation with others similarly engaged.

LLL Results

A typical smoke density vs time set of curves for red oak, the standard material used in the Steiner Tunnel, is shown in Figure 3. Note that under nonflaming conditions in a closed chamber (or room), smoke density rises slowly first and then more rapidly to a value at which it is considered to be very dense. Under flaming exposure, a considerably lower value is achieved. By plotting the maximum smoke densities obtained against various ventilation rates, the values for red oak are typically shown in Figure 4. As can be seen, it is quite easy to clear away the smoke under the flaming condition, but it is less so under the nonflaming exposure.

On Figure 5 are shown the smoke density-time curves for three, solid, one-fourth inch thick transparent acrylics. Under nonflaming exposure the fire retardant

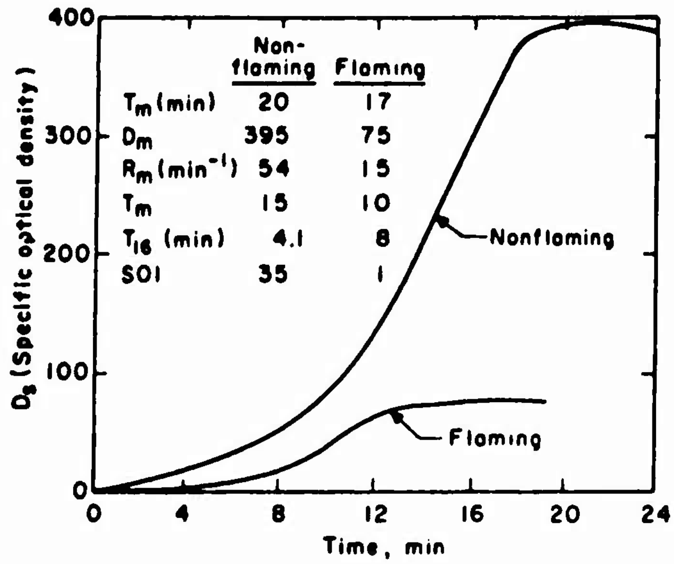


Figure 3. *Typical smoke development from red oak.*

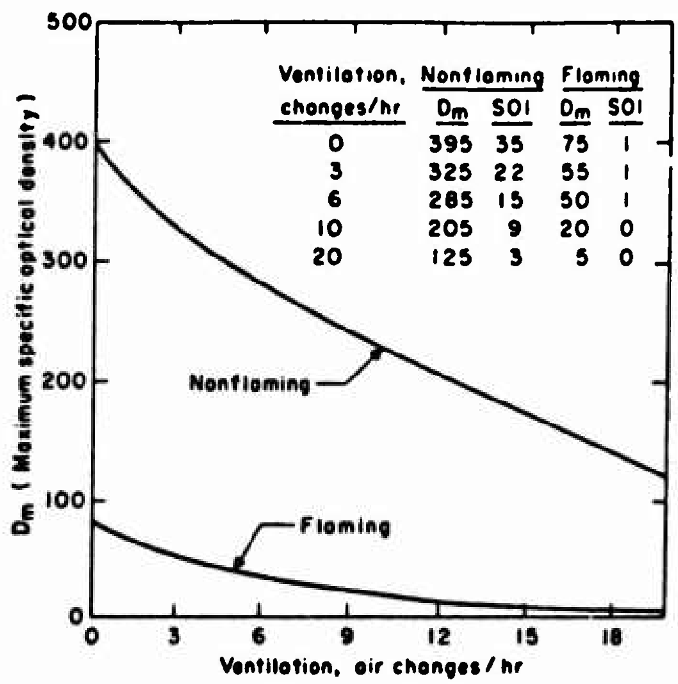


Figure 4. *Effect of ventilation on maximum smoke density of red oak.*

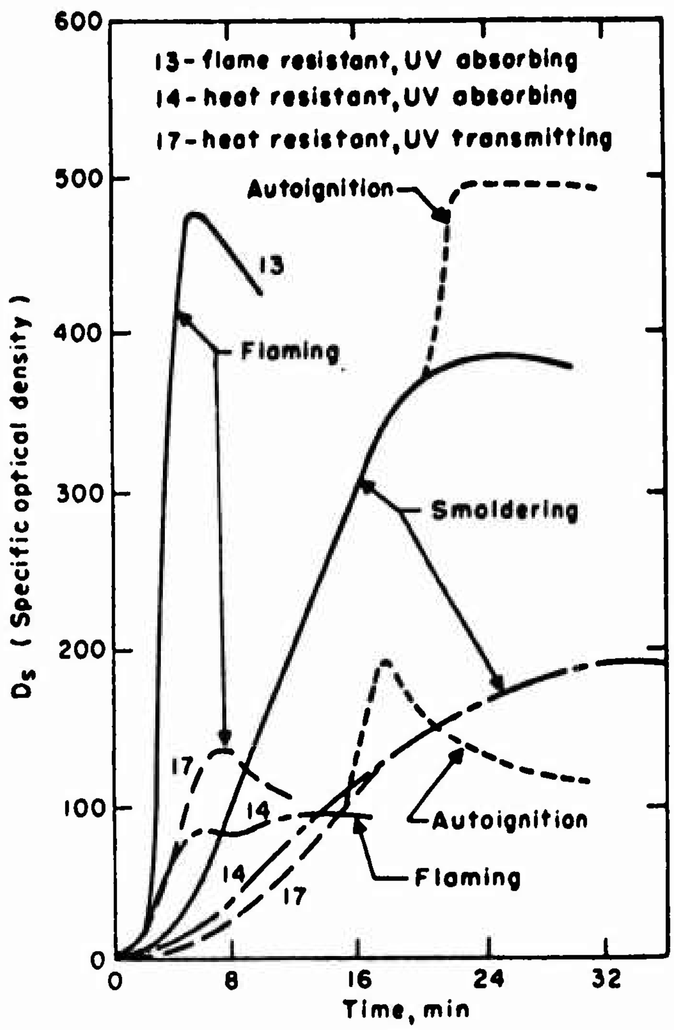


Figure 5. *Smoke development from three clear acrylics.*

variety exhibited a curve similar to that of red oak. The other two materials showed a smoke of noticeably less density. Under flaming exposure, the fire retardant variety quickly yielded a very dense smoke. The other two smoked as fast but to a smaller degree. Of particular interest is the autoignition tendencies of two of the materials. In over half the tests made, these samples ejected flaming species as shown onto the coils of the radiant heater and set themselves on fire, thus producing a much denser smoke than when the phenomena did not occur.

In Figure 6 are shown the effects of ventilation on the maximum smoke densities of these acrylics and one transparent styrene material of the same thickness. Note that under the pyrolysis conditions, the acrylics behaved in a matter similar to wood. The maximum smoke density attained is rapidly lowered with increasing ventilation. On the other hand, ventilation does not seem to help the smoke density under flaming conditions. In fact for two of the materials, a

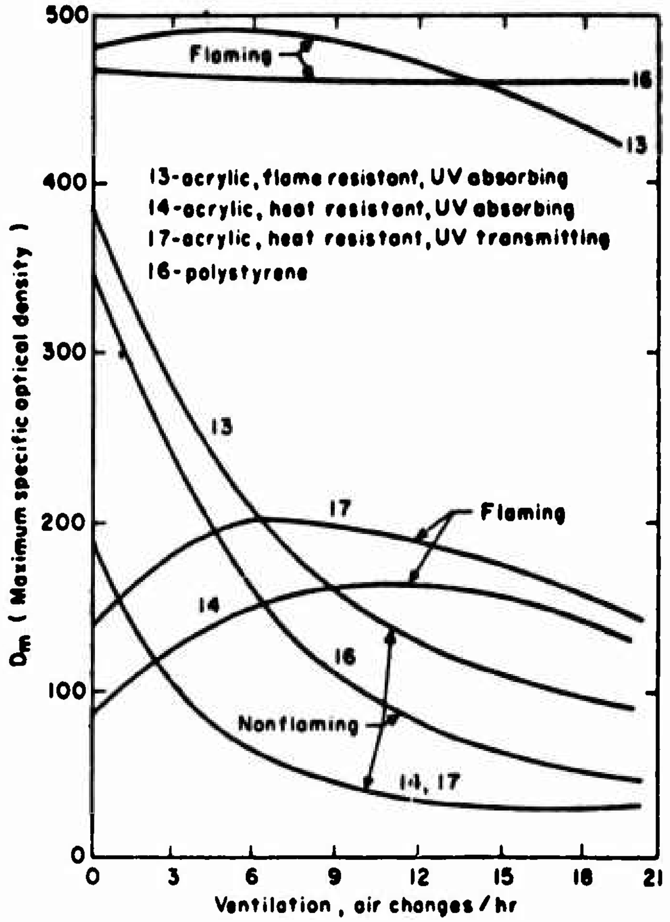


Figure 6. *Effect of ventilation on maximum smoke density of three acrylics and one styrene.*

moderate ventilating rate of 6 air changes an hour seemed to increase the maximum smoke density. In the cases of the styrene material and the fire-retardant acrylic, ventilation was completely ineffective in clearing away the smoke as far as maximum density is concerned.

Figure 7, showing the smoke development from clear, rigid polyvinyl chloride in two thicknesses, is interesting in that under the flaming condition it does not seem to make any difference whether the materials is one-fourth or one-eighth inch thick.

The data shown on Figure 8 point up the need for testing materials systems in the manner in which they are going to be used. Curves obtained show the smoke-density time curves, for a polyester/epoxide coating on three-eighth inch gypsum wallboard. Under the nonflaming exposure, the results were as expected. The

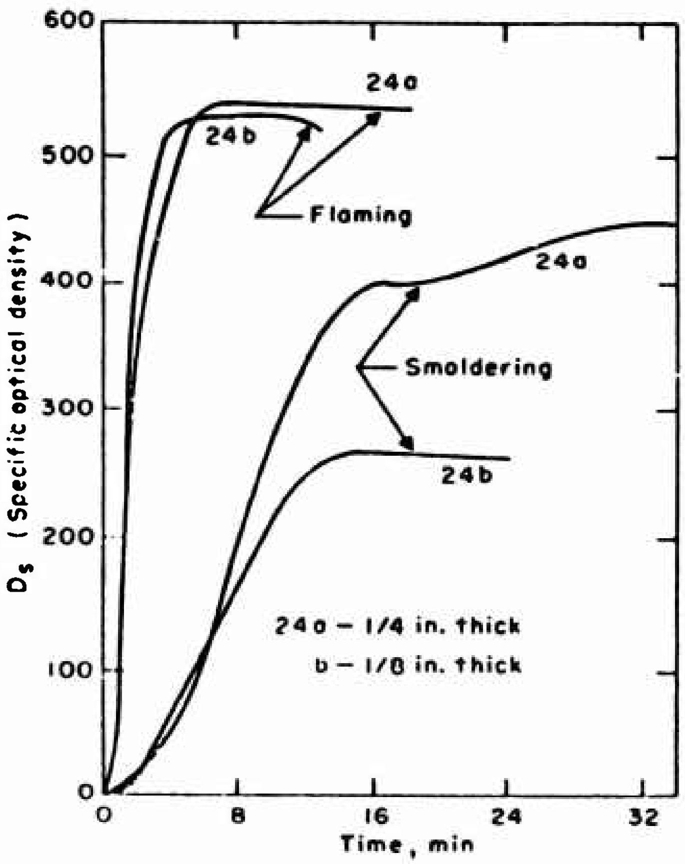


Figure 7. Smoke development from a clear, rigid polyvinyl chloride.

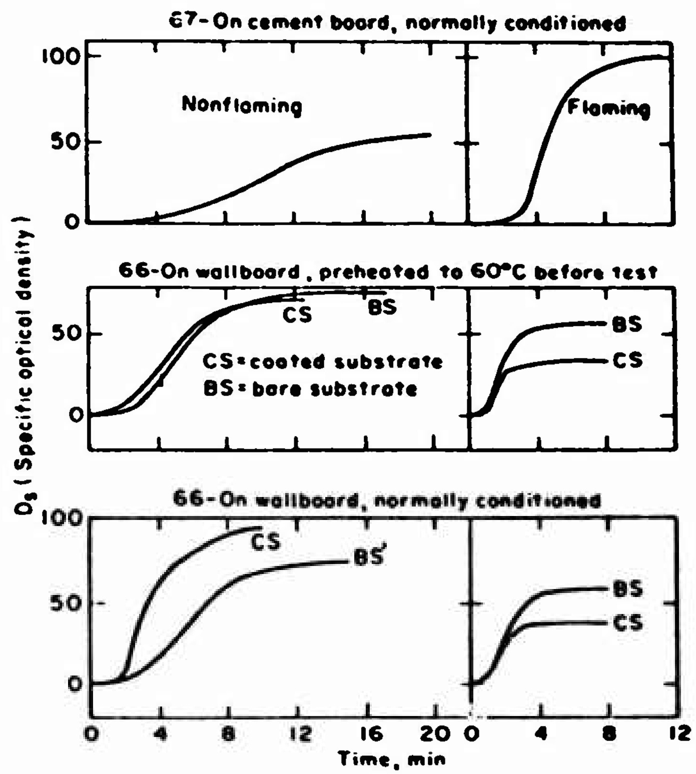


Figure 8. Smoke development of polyester/epoxide coating.

coated specimen yielded a slightly denser smoke than the bare specimen. However, the opposite was found to be true under flaming exposure when the specimens were tested under the normal conditioning or preheated to 60°C to remove moisture before the test. Tests of the same coating applied to cement board showed somewhat different results. It should be noted that each curve shown represents at least two replicate tests with good agreement between replicates.

As stated above, we have examined and tested over 100 different materials in the LLL smoke chamber. Our findings to date – under the 2.5 W/cm^2 radiant heat flux exposure – can be summarized as follows:

1. Woods, including solid woods, plywood, and other cellulosics, show curves similar to those for red oak in the flaming and nonflaming exposures, both with and without ventilation. However, each particular product or material has its own characteristic maximum smoke density value. An exception should be noted in the case of one wood with two different fire retardant treatments. In this case, denser smokes were obtained under the flaming conditions for the material which had been fire retarded.

2. Plastics may be divided into two broad categories: a few which do not produce visible smoke under either flaming or nonflaming exposure; and the vast majority which can be divided into two further classifications. Of those materials, which do produce smoke, exposure to heat alone yields a broad spectrum of smoke densities. Some behave much like wood, slowly building up to a high density; others will build up fairly rapidly, but to about the same density.

In the presence of heat and flame, however, we have observed two separate phenomena:

(a) plastics which tend to burn cleanly are similar to wood under similar conditions.

(b) Those that do not burn cleanly; i.e., are fire retarded in one way or another, rapidly evolve dense smokes. These are not readily cleared away by ventilating.

A question arises as to how these results may be used. We grant that these data are obtained in a small-scale test and we agree with Christian [10] that, "No single smoke rating number should be expected to define relative smoke hazards of materials in all situations." Furthermore, we point out that the necessarily large-scale correlating tests needed to verify the applicability of the LLL Chamber tests are yet to be done. Nevertheless, we feel that the results can be used with some judgment by employing the nomograph shown in Figure 9 to evaluate the opacity hazard of a materials system. This chart, the original of which was developed by Gross [9], plots the specific optical density of the smoke at the time of interest against the room geometrical factor; i.e., the volume of the room, the area of the material smoking, and the light path or the distance between the observer's eye and an exit sign.

By putting in the appropriate numerical values for the area of the material in

its intended application, the specific optical density for the time of interest as determined by a test, and including the volume of the room and the distance from an observer or victim, as you please, to the exit sign; one can determine whether or not an opacity hazard exits from smoke involving this material.

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(b) D. Gross, J. J. Loftus and A. F. Robertson, "Method for Measuring Smoke from Burning Materials: *American Society for Testing and Materials,* (Philadelphia STP – 422, 1966) Fire Test Methods – Restraint and Smoke.

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APPENDIX I

SMOKE MEASUREMENTS AND GAS ANALYSIS

FROM THERMAL DEGRADATION OF

141 AIRCRAFT MATERIALS:

Excerpt from D. Gross, ***et al., Smoke and Gases Produced by Burning Aircraft Interior*** **Materials, NBS Building Science Series 185 Washington, D. C.: U.S. Government Printing Office (1969).**

3.2 Smoke Measurements

Smoke measurements are summarized in appendix 3 in terms of the maximum smoke accumulation (D_m), the maximum rate of smoke accumulation (R_m) and the time (t_c) to reach a specific optical density of 16 for both flaming and smoldering exposure. These results represent averages of duplicate tests (with few exceptions). For D_m values up to 200, the standard deviation was 11.8 for flaming and 9.2 for nonflaming tests. Smoke buildup curves for typical flaming and smoldering tests on selected types of materials are shown in appendix 4.

A wide range of D_m values was measured. Slightly more than 15 percent of the materials produced smoke corresponding to a $D_m = 16$ or less, for both flaming and smoldering exposures. These included materials composed of glass, asbestos, aromatic polyamide, polyimide plus others, but many of these materials were very thin (light-weight). D_m values in excess of 200 were recorded for flaming and smoldering exposures on approximately 20 percent of the materials.

For flaming exposure of 140 materials, frequency distribution histograms of the maximum smoke values are shown in Figure 3 for all materials, and in Figure 4, within the classification groups: (a) fabrics, (b) rugs, (c) sheets, films, and laminates, and (d) pads, insulations, and assemblies. Of the materials in the $D_m \leqslant 16$ category, 16 were fabrics, 6 were sheets or films, and 4 were glass or asbestos fiber insulations.

With one exception, all materials in the $D_m \leqslant 16$ category under flaming conditions were also $D_m \leqslant 16$ under nonflaming conditions.

Figures 5, 6, and 7 comprise a complete histogram showing smoke and toxic gas concentrations for flaming and nonflaming exposures on each material based on the data in appendix 3. Materials have been arranged according to classification by groups, by composition, and by generally increased weight within each subgroup.

It should be noted that only the "front" side of a material was exposed, and that specimens exhibited a very wide range in their physical and thermal behavior during flaming and nonflaming exposure. Materials which melted at fairly low temperatures, including nylon, polysulfone, and polyethylene, flowed to the bottom or dripped off the sample holder in varying degrees, resulting in less smoke. Some materials evaporated fairly rapidly before extensive decomposition or combustion took place. All urethane foam materials produced more smoke under smoldering exposure than with flaming exposure, except in one instance where the material was noted to shrink into a corner of the holder and was, therefore, subjected to less radiation. Rubber (chloroprene), ABS, methacrylate, and PVC materials nearly always produced more smoke under flaming exposure. Under thermal radiation exposure alone, elastomers generally formed a bell-shaped protrusion at their center through which gaseous products streamed out rapidly. The maximum smoke level depends upon the thickness (and density) of the specimen, and for some materials D_m may be expected to increase with thickness but not always in direct proportion [3].

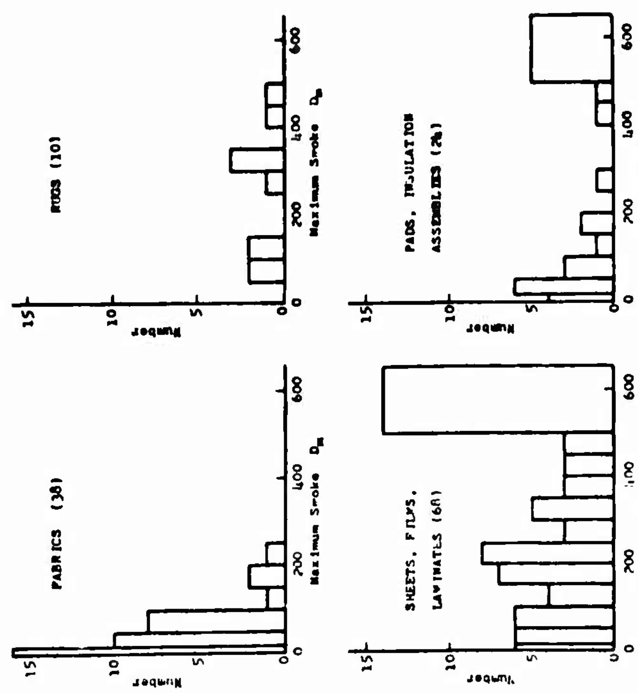


FIGURE 4. *Frequency distribution of maximum smoke values by groups. Flaming exposure—140 materials.*

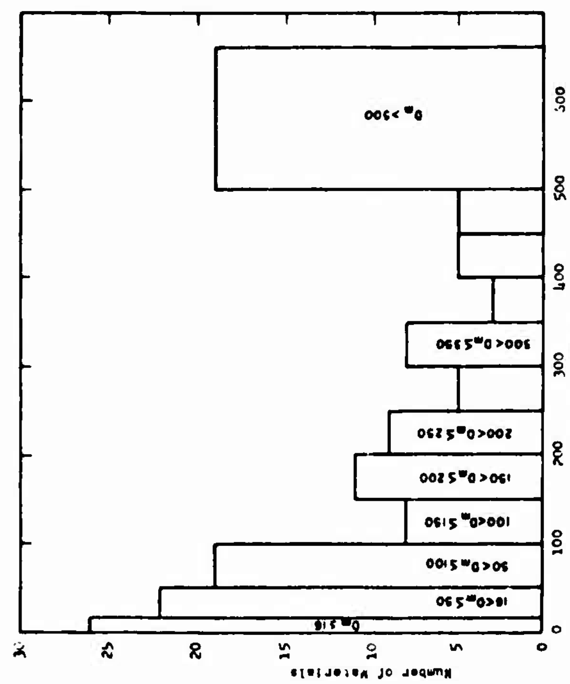


FIGURE 3. *Frequency distribution of maximum smoke values. Flaming exposure—140 materials.*

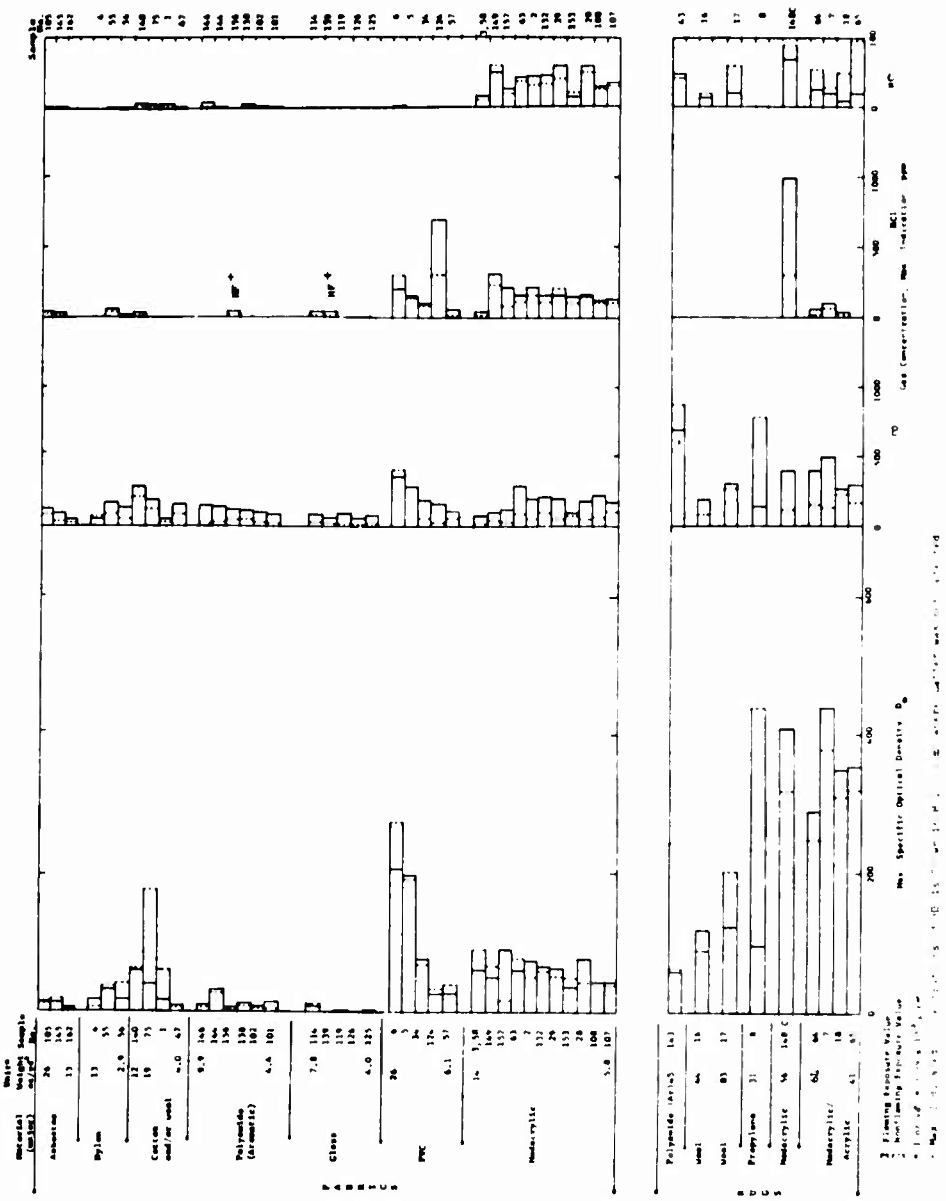


FIGURE 5. *Smoke and gas concentrations for individual materials—fabrics, rugs.*

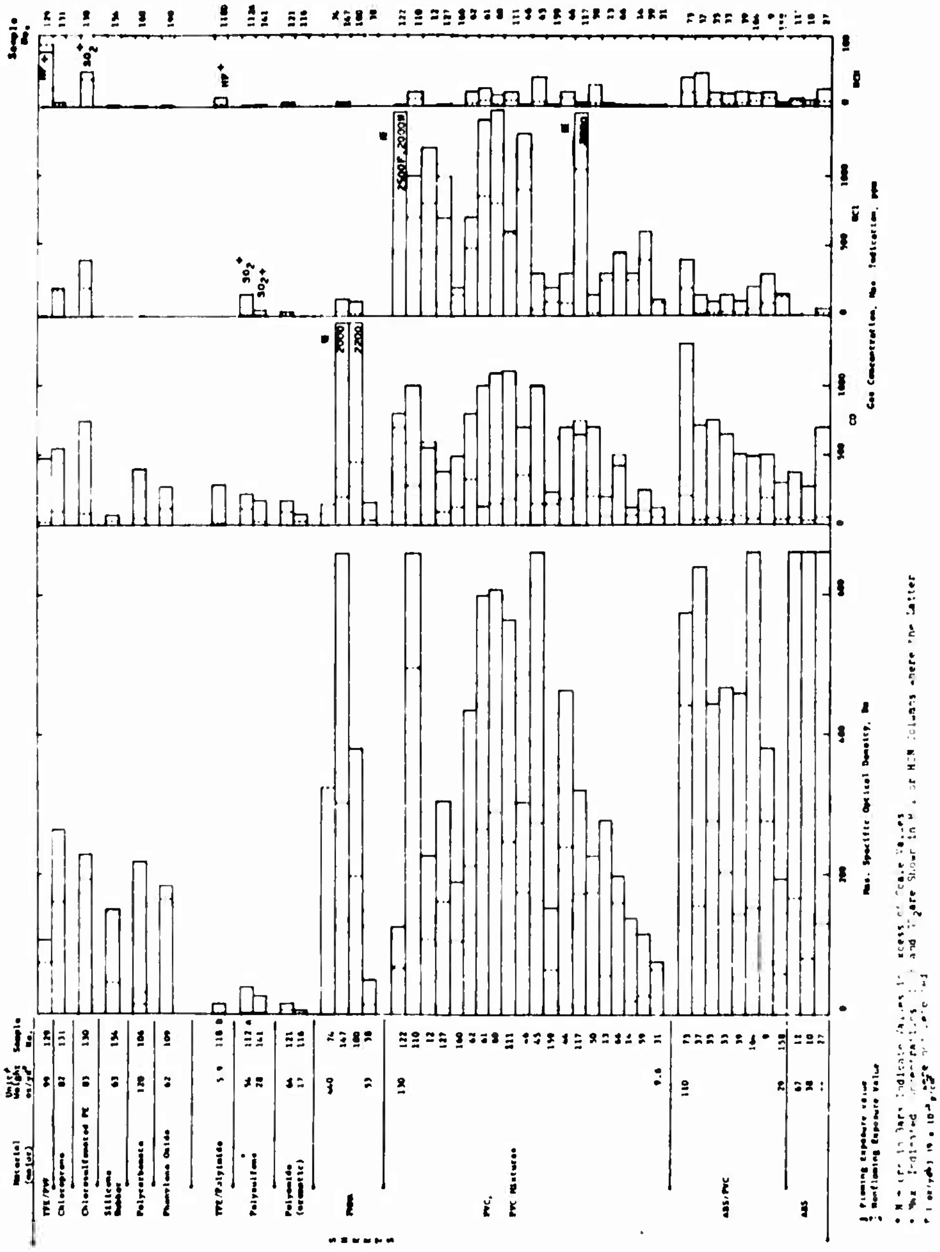
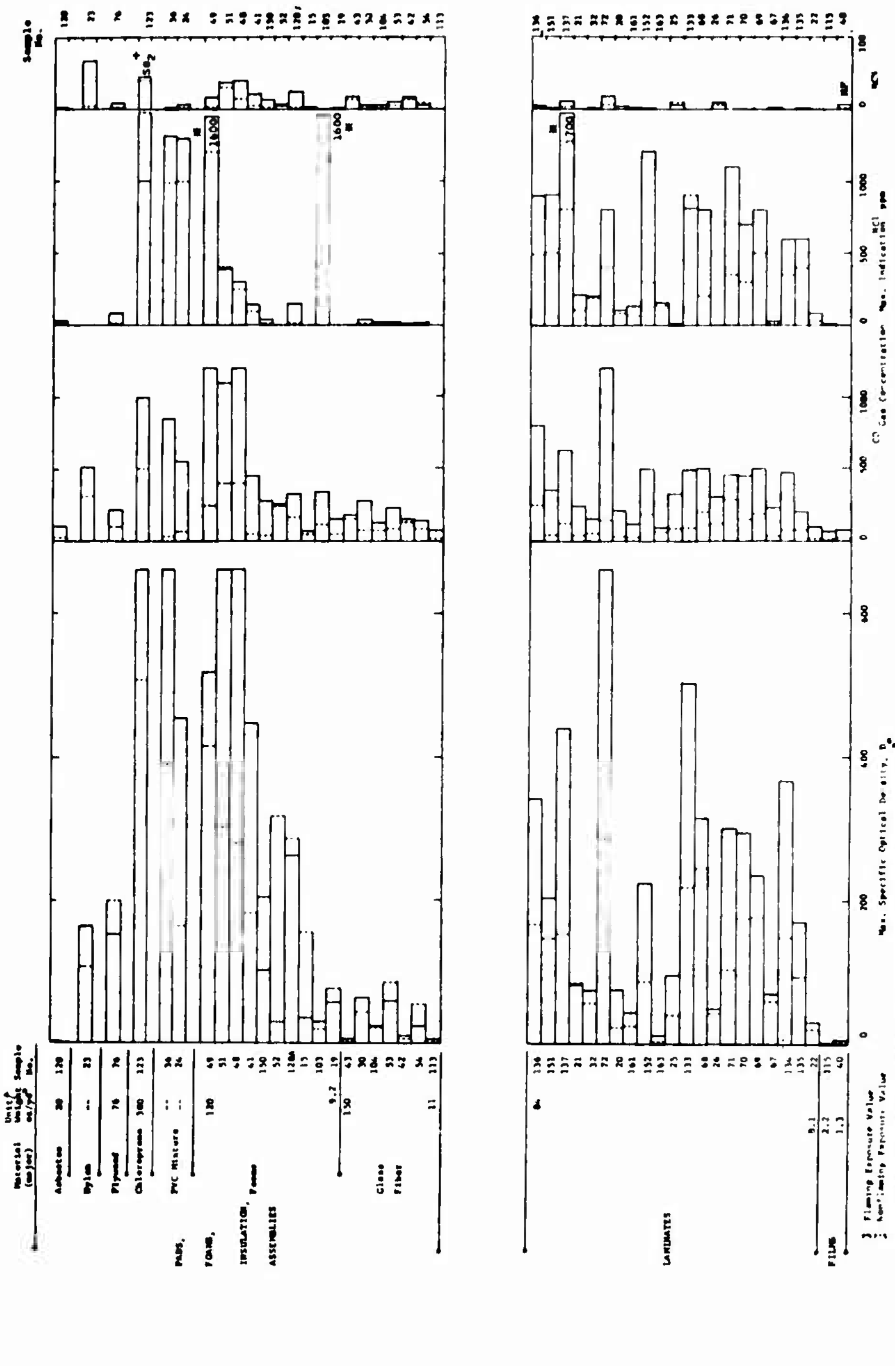


FIGURE 6. Smoke and gas concentrations for individual materials—sheets.



*Numbers in Bars Indicate Values in Excess of Scale Values
+Max. Indicated Concentration of SO_2 is shown in HCN Column Where Latter was not Detected
+1 oz. yd. = 3.39 x 10 g/cm²

FIGURE 7. *Smoke and gas concentrations for individual materials—assemblies, laminates, films.*

3.3 Gas Analysis

"Maximum" indicated concentrations of gases are listed in appendix 3 along with the smoke data. These values are based on the average of two separate determinations, except that additional tests were made where large discrepancies (greater than a factor of 2) between duplicate values were obtained. Unlike the measurement of optical density of smoke, which is recorded continuously to obtain a maximum, the concentrations of selected components was measured periodically. Particularly for components which change rapidly, therefore, the indicated concentration values may not necessarily be the true maximum values. For the materials tested, the highest indicated concentrations were 2200 ppm CO, 2500 ppm HCl, and 90 ppm HCN. These concentrations refer to the same exposed area of specimen and chamber volume used, but to a wide range of specimen weights.

Since the primary objective of this study was to ascertain approximate values, no extensive efforts were made to improve reproducibility. As a test of reproducibility for a PVC material (specimen No. 44), 5 separate smoldering exposure tests were conducted with the results shown in figure 8. This figure shows the five

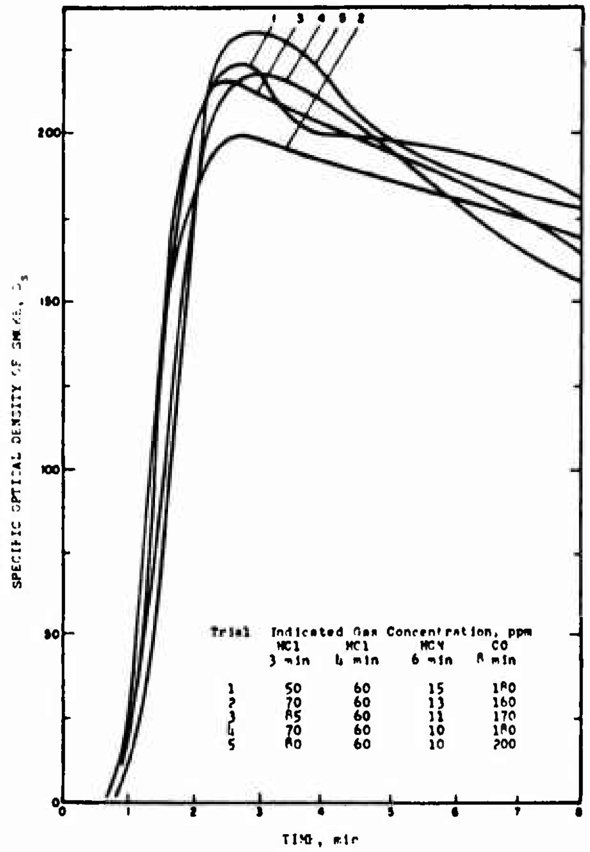


FIGURE 8. *Reproducibility of smoke and gas concentration indications. Sample No. 44 (PVC/PVA/ABS) nonflaming exposure.*

replicate smoke curves and a tabulation of indicated gas concentrations at specific times during each test. The measurement ranges were on the order of ± 20 percent for CO and HCN and ± 30 percent for HCl, and such variations may be considered typical of the maximum indicated concentration values under the test conditions.

Because the plastic materials studied were from many manufacturers and generally contained plasticizers, fillers, and othe;additives, it is difficult to relate quantitatively gaseous product concentrations with polymer composition. In general, HCl was produced by polyvinyl chloride and modacrylic materials, HF from polyvinyl fluoride, HCN from wool, urethane, ABS, and modacrylics, and SO_2 from polysulfone and rubber materials. CO was produced by almost all the samples in varying amounts depending on the type of material.

It has been shown [5] that the amount of a given gas produced during pyrolysis and its rate of generation are strongly temperature dependent. Thus, any materials or processes which affect the temperature profile across the specimen (e.g. fillers and plasticizers which produce surface crusting, intumescence, etc.), could readily influence the concentration of gaseous products. For certain materials, higher concentrations of some gases may be produced under conditions of insufficient air, e.g. 10 per cent oxygen [6].

Sampling was performed sequentially, proceeding generally from HCl and HF to HCN to CO, and was initiated when optical density of the smoke approached its peak. This procedure was followed because of the fairly rapid decay in halogen acid concentration resulting from adsorption on (and reaction with) moisture, smoke particles, and chamber surfaces. To facilitate subsequent data comparison, sampling for HCl and HF was generally initiated at the beginning of the minute close to the maximum smoke level, and at 2-min intervals thereafter for other gases.

Gas temperature at the sampling tube inlet generally ranged from 46 to 52°C (115 to 126°F), the higher temperatures occurring during flaming tests on heavier materials. Due to the cooling tests on heavier materials. Due to the cooling effect of the precleaning layers of the indicator tubes, the temperature of the gases passing the indicating layers were within the prescribed maximum temperature limits. The sampling rate was generally unaffected by either the elevated temperature of gases or by heavy smoke particle concentrations.

Hydrogen chloride is generally released rapidly during combustion or pyrolysis of polyvinyl chloride, modified acrylics and other retardant-treated materials [7, 8]. Maximum levels were generally higher under flaming compared to smoldering exposure conditions presumably due to the higher temperature involved and the resultant greater rate of release. The HCl concentration changed rapidly as a result of its high reactivity, solubility in water, and adsorption on smoke particles and wall surfaces. The type of surface as well as the total area of the interior walls have a prounced influence on the adsorption and settling (or decay) rate of HCl and smoke. To illustrate the decay of both HCl and CO, a suitable concentration of the pure component was metered into the bottom of the chamber under both smoke-free ($D = 0$) and smoke-filled conditions. Figure 9 shows the indicated concentra-

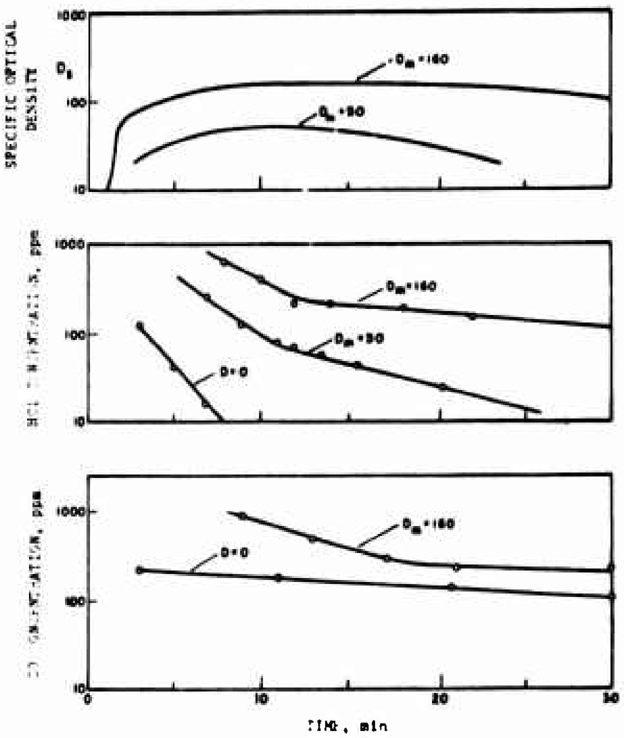


FIGURE 9. *Comparative decay in HCl and CO concentrations for several smoke density levels.*

Top: Smoke, nonflaming exposure, 2 selected PVC/PVA materials

Center: HCl concentration. Prior to taking readings, 220 cm^3/min of HCl was introduced in chamber over 3-min period

Bottom: CO concentration. Prior to taking readings, 190 cm^3/min of CO was introduced in chamber over 3-min period

tions of HCl and CO. In these tests involving smoldering specimens only, the gas concentration levels are obviously higher because a portion of the gas is introduced by combustion. The decay rates are also higher.

5. Conclusions

Based upon the tests performed and an evaluation of the results, the following conclusions have been reached:

1. Materials currently used as interior furnishings for aircraft cabins, and those being considered for future use, vary considerably in their production of smoke and potentially toxic products under simulated fire conditions.
2. The laboratory test method for generating smoke and measuring its optical density appears to be a useful tool for the quantitative classification of materials, and for the possible establishment of revised fire safety standards and criteria for controlling smoke production. Optical density is the single most characteristic measure of the visual obscuring quality of a smoke.

3. For evaluating smoke production, both smoldering and active flaming conditions should be considered. For the majority of materials, more smoke was produced during the flaming exposure test. However, certain materials produced significantly more smoke in the absence of open flaming.
4. Within the limitations and assumptions cited, the specific optical density of smoke measured in the laboratory may be extrapolated to cabin volumes and surface areas of combustible furnishings in order to provide guidelines for cabin area limitations, or to estimate time periods available for escape or defensive action.
5. Indications of the concentrations of potentially toxic combustion products can be conveniently and inexpensively obtained during the smoke production test using calibrated commercial colorimetric tubes; however, these are suitable only where interferences by other gases are absent, and where precision is not of primary importance The specific ion electrode is also a convenient method of measuring the concentrations of halogen acid gases. Furthermore, if an attempt is made to relate the indicated concentrations measured in the smoke chamber in terms of toxicological limits, caution must be exercised. It is essential that proper consideration be given to (a) scaling of the areas and volumes in the proposed situation, (b) the integrated dosage where concentration varies with time, (c) the synergistic effects of several components (and smoke particles), and (d) the effects of relative humidity, elevated temperature, stratification, adsorption on surfaces, and physiological factors not considered in this study.

8. Appendix 2. Material Description

Abbreviations

Code	Designation	Composition
F1,F2—Fabric (uncoated, coated)	C Coated	ABS Acrylonitrile/butadiene/styrene
R1,R2—Rug (unpadded, padded)	UC Uncoated	PETP Polyethylene terephthalate polyester
S1,S2,S3—Sheet (flexible, semi-rigid, rigid)	F Flexible	PMMA Poly methyl methacrylate
L1,L2,L3—Laminate (flexible, semi-rigid, rigid)	SR Semi-rigid	PVA Poly vinyl acetate
	R Rigid	PVC Poly vinyl chloride
	P Padded	
	UP Unpadded	
	FR Fire-retardant treated	

No.	Code	Thickness	Unit* weight	Color and surface	Designation	Present or intended use	Material identification
		Inch	*oz/yd²*				
1	F-1	0.035	11	Light-blue	Fabric (UC)	Drapery	Wool/cotton (75:25).
2	F-1	0.030	9.6	Light-blue	Fabric (UC)	Drapery	Modacrylic.
3	F-1	0.055	14	Blue (multi-color pattern)	Fabric (UC)	Drapery	Modacrylic/nylon/cotton.
4	F-1	0.050	13	Tan Corduroy	Fabric (UC)	Upholstery	Polyamide (nylon type).
5	F-2	0.030	12	Blue Matte	Fabric (C)	Upholstery	Polyvinylchloride/methyl methacrylate/ester plasticizer on cotton.
6	F-2	0.045	26	Gold Matte	Fabric (C)	Upholstery	Polyester plasticizer (phthalate-type), possible PVC, on cotton.
7	R-2	0.33	62	Blue/gray Loop	Rug (P)	Flooring	Pile: Modacrylic/acrylic. Backing: Polyester fiber. Pad: Polyester urethane foam.
8	R-1	0.18	31	Blue/green Loop	Rug (UP)	Flooring	Pile: Copolymer poly(propylene-butylene). Center: Cellulosic. Backing: Polyethylene.

continued

No.	Code	Thickness	Unit* weight	Color and surface	Designation	Present or intended use	Material identification
9	S-1	0.046	46	Tan Matte	Sheet (F)	Panel and door covering	PVA/ABS, china clay pigmented possible PVC.
10	S-2	0.045	38	Dark gray Matte	Sheet (SR)	Food trays, window frames	ABS (~25%: 10%: 65%).
11	S-3	0.080	67	Green Polished	Sheet (R)	Food trays, window frames	ABS (~25: 10: 65).
12	S-3	0.080	81	Tan Matte	Sheet (R)	Ceilings, seat panels	Copolymer: PVC/poly methyl methacrylate (~95: 5).
13	S-2	0.030	26	Gold Shiny	Sheet (SR)	Trim	PVC and polyvinyl acetate base with some ABS plastic added. Film: Polyethylene terephthalate (PETP) polyester.
14	S-2	0.020	20	White/green Smooth	Sheet (SR)	Sides, ceiling, seat panels	Polyvinyl chloride/vinyl acetate (~89: 11).
15	S-1	4.0	110	White Open cell	Foam (F)	Seat cushion padding	Polyether urethane.
16	R-1	0.22	44	Blue Loop	Rug (UP)	Flooring	Wool.
17	R-2	0.43	83	Multi-color Loop	Rug (P)	Flooring	Pile: Wool. Back: Polyester. Pad: Urethane foam.
18	R-1	0.22	59	Black/gray Loop	Rug (UP)	Flooring	Modacrylic/acrylic.
19	S-1	0.21	9.2	Green Open cell	Pad (F)	Carpet underlay	Polyester urethane foam.
20	L-3	0.042	68	Gold Embossed	Laminate (R)	Panels—Overhead and sides	Face: Polyvinyl acetate with trace of ABS covered with PETP polyester. Back: Aluminum sheet.
21	L-3	0.044	79	Tan Dull, brushed	Laminate (R)	Panels—Overhead and sides	Face: Vinyl chloride/acrylate copolymer (80: 20). Back: Aluminum sheet.
22	L-1	0.009	8.1	Aluminum Matte, shiny	Laminate (F)	Window shades	Face: PETP Polyester. Back: Vinyl acetate, PVC copolymer.

* 1 oz/yd^2 = 3.39x10^{-3} g/cm^2.

Materials Description—Continued

No.	Code	Thickness	Unit weight	Color and surface	Designation	Present or intended use	Material identification
		Inch	*oz/yd²*				
23	A	Irregular		White Smooth	Assembly (molded)	Assist handles	Polyamide (nylon type).
24	A	Irregular		Green Smooth	Assembly (molded)	Seat track covers	Polyvinyl chloride, ABS terpolymer (94:6).
25	L-3	0.035	30	Gray Glossy	Laminate (R)	Galley area	Face: Melamine formaldehyde. Back: Urea formaldehyde.
26	L-3	0.032	35	Blue Glossy	Laminate (R)	Galley area	Face: Melamine formaldehyde. Back: Urea formaldehyde.
27	S-2	Irregular		White	Sheet (SR)	Passenger service units	Rigid part: ABS (40:40:20) possible PVC. Flex part: Plasticized PVC possible some vinyl acetate.
28	F-1	0.028	8.0	Tan/gold trace	Fabric (UC)	Drapery	Modacrylic.
29	F-1	0.030	9.3	Turquoise, gold trace	Fabric (UC)	Drapery	Modacrylic.
30	A	0.41	62	Tan Matte	Assembly (honeycomb)	Ceilings, bulkheads	Face: Coated glass fabric (Polyester or cross-linked Acrylic). Core: Paper honeycomb. Back: Plastic-impregnated glass fabric
31	S-1	0.010	9.6	White Matte	Sheet (F)	Lowered ceilings	Vinyl chloride/acrylate, possible Polyvinyl acetate.
32	L-3	0.045	75	Light blue Matte	Laminate (R)	Lowered ceilings	Vinyl chloride/acrylate copolymer film on aluminum sheet.
33	S-3	0.093	91	White Matte	Sheet (R)	Hatrack	ABS (40:40:20), possible PVC.
34	F-2	0.010	10	Tan Smooth	Fabric (C)	Underside hatrack bullnose	Vinyl chloride/Acrylate copolymer on glass fabric (28%) plus pigment (13%).
35	S-3	0.096	90	Gray Dull	Sheet (R)	Toilet floor pans	ABS (40:40:20), possible PVC.
36	A	0.063		Tan Smooth	Assembly (molded)	Ceiling panel joint	Plasticized PVC. Plasticized di-(2 ethyl-hexyl) phthalate.

No.	Code	Thickness	Unit weight	Color and surface	Designation	Present or intended use	Material identification
37	S-3	0.097	92	White Matte	Sheet (R)	Magazine rack	ABS (40:40:20)/PVC.
38	S-3	0.063	53	Clear Polished	Sheet (R)	Window pane	Methyl methacrylate/Methyl acrylate copolymer (90:10).
39	S-3	0.064	62	Tan Matte	Sheet (R)	Control panel	ABS (40%:40%:20%), possible PVC.
40	S-1	0.002	1.3	Clear Smooth	Film (F)	Protective coating	Polyvinyl fluoride.
41	A	0.35	95	Tan	Assembly (molded)	Bulkhead	Face: ABS. Back: Polyether urethane foam.
42	A	1.3	35	Yellow Fibrous	Pad	Insulation	Glass fiber (plus organic binder).
43	A	2.5	150	Yellow Fibrous	Assembly	Insulation	Glass fiber with lead sheet.
44	S-1	0.046	44	Tan Matte	Sheet (F)	Seat panels	PVA/ABS, china clay pigmented, possible PVC.
45	S-3	0.063	60	Tan Matte	Sheet (R)	Seat panels	PVC/ABS.
46	S-3	0.057	55	White Matte	Sheet (R)	Seat panels	PVC/PMMA (90:10).
47	F-1	0.012	4.0	White Matte	Fabric (UC)	Lining for seat pads	Cotton.
48	A	0.57	82	Tan Matte	Assembly	Seat panels	Face: PVC/ABS Back: Polyurethane.
49	A	0.52	120	White Matte	Assembly	Seat panels	Face: PVC/PMMA (90:10). Back: Urethane foam—polyether type.
50	S-3	0.60	35	White Open cell	Sheet (R)	Seat construction	Urethane foam—polyether type.
51	S-2	1.0	88	White Closed cell	Foam (SR)	Seat construction	Plasticized foam containing PVC/PVA and nitrile groups.
52	S-1	4.0	90	White Open cell	Pad (F)	Seat construction	Urethane foam—polyether type (FR).
53	A	3.0	44	Tan Smooth	Assembly	Insulation	Face: Filled rubber on Nylon 6-6 fabric. Back: Glass fiber batt

Materials Description--Continued

No.	Code	Thickness	Unit weight	Color and surface	Designation	Present or intended use	Material identification
		Inch	*oz/yd²*				
54	A	1.3	28	Blue Smooth	Assembly	Insulation	Face: Organic-filled nylon fabric. Back: Glass fiber batt.
55	F-2	0.004	4.2	Tan Smooth	Fabric (C)	Cover for insulation batt	Polyethylene film over nylon fabric (filled rubber).
56	F-2	0.004	2.9	Light blue Smooth	Fabric (C)	Cover for insulation batt	Organic-filled nylon 6-6 fabric.
57	F-2	0.006	6.1	Green Smooth	Fabric (C)	Bulkhead assembly lining	Plasticized PVC on Glass fabric.
58	F-1	0.054	14	Bluish multicolored weave	Fabric (UC)	Drapery	Modacrylic/nylon/cotton.
59	S-1	0.020	16	White/color pattern	Sheet (F)	Partitions	PVC/PVA (89:11).
60	S-3	0.060	64	Gold Glossy	Sheet (R)	Side panels	Plasticized PVC/PVA with ABS.
61	S-3	0.060	62	Blue Glossy	Sheet (R)	Side panel	PVC/PVA (Small amount of ABS).
62	S-3	0.069	70	White with pattern	Sheet (R)	Window panel	Polyvinyl butyral film on PVC/PVA (90:10).
63	F-1	0.030	9.5	Yellow/gold trace	Fabric (UC)	Drapery	Modacrylic/polyester.
64	R-1	0.33	64	Blue/green Loop	Rug (UP)	Flooring	Modacrylic/acrylic.
65	R-1	0.23	41	Brown/white/black loop	Rug (UP)	Flooring	Modacrylic/acrylic.
66	S-1	0.032	25	Tan/yellow Burlap	Sheet (F)	Sidewall	Plasticized PVC.
67	L-2	0.022	24	White Burlap	Laminate (SR)	Baggage liner	Polyester plastic filled glass fiber fabric.
68	L-2	0.038	34	Blue/white/yellow Simulated fabric	Laminate (SR)	Sidewall, partition liner	Face: PVC/PVA (89:11). Back: Cotton fabric and paper

No.	Code	Thickness	Unit weight	Color and surface	Designation	Present or intended use	Material identification
69	L-2	0.026	24	Blue/white Simulated fabric	Laminate (SR)	Sidewall, partition liner	PVC/PVA.
70	L-2	0.031	28	Gray Glossy	Laminate (SR)	Sidewall, partition liner	Face: Acrylate. Back: PVC/PVA.
71	L-2	0.033	31	Tan/white Embossed	Laminate (SR)	Sidewall, partition liner	PVC/PVA (93:7).
72	L-3	0.075	71	Red Matte	Laminate (R)	Door liners	Face: PVC/PVA. Back: ABS/PVC.
73	S-3	0.11	110	Gray Glossy	Sheet (R)	Cockpit liner	ABS/PVC.
74	S-3	0.50	440	Clear Glossy	Sheet (R)	Window panes	Methyl methacrylate.
75	F-1	0.060	19	Turquoise Corrugated	Fabric (UC)	Upholstery	Cotton/nylon (small amount of polyester).
76	A	0.38	76	White Smooth	Assembly (honeycomb)	Ceiling panel	Face: Acrylic/vinyl coating over plywood (paper). Core: Paper with [illegible] esolformaldehyde resin adhesive.
100	S-3	0.18	180	Clear Polished	Sheet (R)	Window panes	Methyl methacrylate.
101	F-1	0.015	4.4	White	Fabric (UC)	Drapery	Polyamide (aromatic-type).
102	F-1	0.015	6.1	Green	Fabric (UC)	Drapery	Polyamide (aromatic-type).
103	S-3	1.0	28	White Porous	Foam (R)	Foam insulation	Chlorinated PVC.
104	A	1.0	42	White Embossed	Assembly	Wall Insulation	Glass fabric (100%). Bonded to glass-fiber batt.
105	F-2	0.033	26	Aluminum Glossy	Fabric (C)	High temperature liner	Aluminum on asbestos.
106	S-3	0.13	120	Clear Glossy	Sheet (R)	Window panes fabricated parts	Poly (diphenylol propane) carbonate.

Materials Description—Continued

No.	Code	Thickness	Unit weight	Color and surface	Designation	Present or intended use	Material identification
		Inch	*oz/yd²*				
54	A	1.3	28	Blue Smooth	Assembly	Insulation	Face: Organic-filled nylon fabric Back: Glass fiber batt.
55	F-2	0.004	4.2	Tan Smooth	Fabric (C)	Cover for insulation batt	Polyethylene film over nylon fabric (filled rubber)
56	F-2	0.004	2.9	Light blue Smooth	Fabric (C)	Cover for insulation batt	Organic-filled nylon 6-6 fabric.
57	F-2	0.006	6.1	Green Smooth	Fabric (C)	Bulkhead assembly lining	Plasticized PVC on Glass fabric.
58	F-1	0.054	14	Bluish multi-colored weave	Fabric (UC)	Drapery	Modacrylic/nylon/cotton.
59	S-1	0.020	16	White/color pattern	Sheet (F)	Partitions	PVC/PVA (89:11).
60	S-3	0.060	64	Gold Glossy	Sheet (R)	Side panels	Plasticized PVC/PVA with ABS.
61	S-3	0.060	62	Blue Glossy	Sheet (R)	Side panel	PVC/PVA (Small amount of ABS).
62	S-3	0.069	70	White with pattern	Sheet (R)	Window panel	Polyvinyl butyral film on PVC/PVA (90:10).
63	F-1	0.030	9.5	Yellow/gold trace	Fabric (UC)	Drapery	Modacrylic/polyester.
64	R-1	0.33	64	Blue/green Loop	Rug (UP)	Flooring	Modacrylic/acrylic.
65	R-1	0.23	41	Brown/white/black loop	Rug (UP)	Flooring	Modacrylic/acrylic.
66	S-1	0.032	25	Tan/yellow Burlap	Sheet (F)	Sidewall	Plasticized PVC.
67	L-2	0.022	24	White Burlap	Laminate (SR)	Baggage liner	Polyester plastic filled glass fiber fabric.
68	L-2	0.038	34	Blue/white/yellow Simulated fabric	Laminate (SR)	Sidewall, partition liner	Face: PVC/PVA (89:11). Back: Cotton fabric and paper

No.	Code	Thickness	Unit weight	Color and surface	Designation	Present or intended use	Material identification
69	L-2	0.026	24	Blue/white Simulated fabric	Laminate (SR)	Sidewall, partition liner	PVC/PVA.
70	L-2	0.031	28	Gray Glossy	Laminate (SR)	Sidewall, partition liner	Face: Acrylate. Back: PVC/PVA.
71	L-2	0.033	31	Tan/white Embossed	Laminate (SR)	Sidewall, partition liner	PVC/PVA (93:7).
72	L-3	0.075	71	Red Matte	Laminate (R)	Door liners	Face: PVC/PVA. Back: ABS/PVC.
73	S-3	0.11	110	Gray Glossy	Sheet (R)	Cockpit liner	ABS/PVC.
74	S-3	0.50	440	Clear Glossy	Sheet (R)	Window panes	Methyl methacrylate.
75	F-1	0.060	19	Turquoise Corrugated	Fabric (UC)	Upholstery	Cotton/nylon (small amount of polyester).
76	A	0.38	76	White Smooth	Assembly (honeycomb)	Ceiling panel	Face: Acrylic/vinyl coating over plywood (paper). Core: Paper with cresolformaldehyde resin adhesive.
100	S-3	0.18	180	Clear Polished	Sheet (R)	Window panes	Methyl methacrylate.
101	F-1	0.015	4.4	White	Fabric (UC)	Drapery	Polyamide (aromatic-type).
102	F-1	0.015	6.1	Green	Fabric (UC)	Drapery	Polyamide (aromatic-type).
103	S-3	1.0	28	White Porous	Foam (R)	Foam insulation	Chlorinated PVC.
104	A	1.0	42	White Embossed	Assembly	Wall Insulation	Glass fabric (100%). Bonded to glass-fiber batt.
105	F-2	0.033	26	Aluminum Glossy	Fabric (C)	High temperature liner	Aluminum on asbestos.
106	S-3	0.13	120	Clear Glossy	Sheet (R)	Window panes fabricated parts	Poly (diphenylol propane) carbonate.

Materials Description—Continued

No.	Code	Thickness	Unit weight	Color and surface	Designation	Present or intended use	Material identification
		Inch	*oz/yd²*				
107	F-1	0.013	5.8	White	Fabric (UC)	Drapery	Modacrylic (100%).
108	F-1	0.013	5.9	Orange	Fabric (UC)	Drapery	Modacrylic (100%).
109	S-3	0.080	62	Yellow Glossy	Sheet (R)	Paneling	Poly (phenylene oxide).
110	S-3	0.13	110	Dark gray Matte	Sheet (R)	Paneling	PVC/PMMA plus ABS.
111	S-3	0.060	57	Green Matte	Sheet (R)	Paneling	PVC/PMMA plus ABS
112A B	S-2	0.060 0.020	54 18	Clear Glossy	Sheet (SR)	Fabricated parts	Polysulfone.
113	S-1	0.30	11	White Fluffy	Pad	Seat padding, wall insulation	Glass fiber (100%).
114	F-2	0.010	7.8	White Matte	Fabric (C)	Headliner	Glass fabric coated with acrylic (aromatic plasticizer).
115	S-1	0.0015	2.2	Clear Smooth	Film (F)	Protective cover	Poly (difluorochloroethylene).
116	S-2	0.020	17	Tan Smooth	Sheet (SR)	Panel sub-strate	Polyamide (aromatic type)
117	S-3	0.045	50	White Glossy	Sheet (R)	Paneling	PVC/poly(vinylidene chloride).
118A B C D	S-1	0.002 0.005 0.003 0.005	2.1 5.4 3.5 5.9	Amber Clear Glossy	Sheet (F)	High tempera-ture insula-tion	Polytetrafluoroethylene films over polyimide
119	F-2	0.007	5.0	Blue	Fabric (C)	Headliner	Glass fabric (97%) with organic finish
120	S-2	0.23	20	Gray Fibrous	Pad	Insulation	Asbestos fiber.
121	S-3	0.063	64	Tan Smooth	Sheet (R)	Panel substrate	Polyamide (aromatic type).
122	S-3	0.11	130	Gray Glossy	Sheet (R)	Paneling	Polyvinyldichloride.

No.	Code	Thickness	Unit weight	Color and surface	Designation	Present or intended use	Material identification
123	S-1	4.0	380	Black Open cell	Foam (F)	Seat padding	Chloroprene.
124	F-1	0.012	9.2	Maroon Glossy	Fabric (UC)	Wall covering	Plasticized poly(vinylidene chloride)
125	F-2	0.005	4.0	Light green Glossy	Fabric (C)	Headliner	Glass fabric (97%) with organic finish.
126	F-2	0.006	4.2	Light gray Glossy	Fabric (C)	Headliner	Glass fabric (83%) with organic finish.
127	S-2	0.034	29	Blue Matte	Sheet (SR)	Paneling	Face: Plasticized PVC/PVA (90 10). Back: Polyamide (Aromatic type).
128A	S-1	4.0	89	White Open cell	Foam (F)	Seat padding	Polyether urethane (FR).
B		4.0	67	White Open cell			Polyether urethane.
129	S-1	0.071	99	Black Smooth	Sheet (F)	Elastomer, seals	Copolymer of tetra uoro-ethylene/vinylidene fluoride
130	S-1	0.067	83	Tan Smooth	Sheet (F)	Elastomer, gaskets	Chlorosulfonated polyethylene.
131	S-1	0.065	82	Black Smooth	Sheet (F)	Elastomer, hoses	Chloroprene.
132	F-1	0.028	8.7	Green	Fabric (UC)	Drapery	Modacrylic and metallized fiber (94: 6).
133	L-1	0.040	36	Copper Glossy	Laminate (F)	Dado paneling	Face: Plasticized PVC/PVA. Back: Polyamide (aromatic type) paper
134	L-1	0.032	27	Light tan Glossy	Laminate (F)	Hatrack	Face: Plasticized PVC/PVA and cotton fiber. Back: Polyamide (aromatic type) paper
135	L-2	0.029	26	Blue/white pattern Smooth	Laminate (SR)	Paneling, Bulkhead dividers	Face: PVC/PVA (90 10) Back: Polyamide (aromatic type) paper.
136	L-3	0.099	84	Lt. gray/gold pattern Rough	Laminate (R)	Flooring	Plasticized PVC/PVA. Top coating—mostly plasticized.
137	L-3	0.074	72	Clear/white/blue Smooth	Laminate (R)	Window reveals, dado Seat backs	Plasticized PVC/PVA (90 10) over pigmented ABS, asbestos-filled.

Materials Description—Continued

No.	Code	Thickness	Unit weight	Color and surface	Designation	Present or intended use	Material identification
		Inch	*oz/yd²*				
138	F-1	0.015	5.8	Green Smooth	Fabric (UC)	Drapery (FR)	Polyamide (aromatic type) cotton (50%:50%).
139	F-2	0.007	6.6	White Smooth	Fabric (C)	Headliner, baggage liner	Glass fabric (60%) coated with polyvinylidene fluoride.
140	F-1	0.024	12	White/blue Smooth	Fabric (UC)	Matress ticking (FR)	Cotton.
141	S-2	0.031	28	Cream semi-clear Glossy	Sheet (SR)	Fabricated parts (FR)	Polysulfone.
142	S-3	1.0	12	White Fine grain	Foam (R)	Insulation	(Urea formaldehyde).
143	R-1	0.30	45	Green Loop	Rug (UP)	Flooring	Polyamide (Aromatic type).
144	F-1	0.035	11	Green/white/orange	Fabric (UC)	Upholstery	Polyamide (Aromatic type).
145	F-2	0.031	18	Silver Reflective	Fabric (C)	Insulation, baggage liner	Aluminum/polyester film on asbestos fabric.
146	F-1	0.035	9.9	White	Fabric (UC)	Upholstery, drapery	Polyamide (more Aromatic groups than 143 and 144).
147	S-3	0.23	210	Clear Glossy	Sheet (R)	Window panes, fabricated parts	Poly methyl methacrylate.
148	R-1	0.25	56	(A) Blue (B) Brown (C) Green Loop	Rug (UP)	Flooring	Pile: Modacrylic (100%).
149	F-1	0.15	10	Cream Fluffy	Fabric (UC)	Blanket	Modacrylic (100%).
150	S-1	4.0	89	White Open cell	Foam (F)	Seat padding (FR)	Polyether urethane.
151	L-3	0.054	75	Light tan Matte	Laminate (R)	Paneling	Plasticized PVC/PVA on aluminum sheet.

No.	Code	Thickness	Unit weight	Color and surface	Designation	Present or intended use	Material identification
152	L-2	0.057	52	Light blue Matte	Laminate (SR)	Paneling	Face (blue): PVC/PVA (89:11). Back (tan): PVC/PMMA (90:10).
153	F-1	0.033	6.8	White Open weave	Fabric (UC)	Casement drapery	Modacrylic/rayon/poly(vinylidene chloride) 20%.
154	S-1	0.11	63	Red Closed cell	Sheet (F)	Padding	Silicone rubber.
155	S-3	0.060	53	Clear Glossy	Sheet (R)	Window panes Fabricated parts	Polycarbonate.
156	F-2	0.007	6.3	White Smooth	Fabric (C)	Headliner	Poly(vinylidene fluoride) coating, on Polyamide (aromatic type) fabric.
157	F-1	0.035	10	White	Fabric (UC)	Drapery	Modacrylic (100%).
158	S-2	0.028	29	Cream Glossy	Sheet (SR)	Panels, fabricated parts	PVC/ABS (94:6).
159	S-2	0.034	34	Olive Glossy	Sheet (SR)	Panels, fabricated parts	PVC/acrylic (90:10).
160	S-3	0.055	65	White Glossy	Sheet (R)	Panels, fabricated parts	Styrene/polyester, fiberglass—reinforced (25%) TiO_2 pigment.
161	L-3	0.032	57	Wood grain pattern Smooth	Laminate (R)	Panels, interior finish	PVC/acrylic on aluminum sheet.
162	F-1	0.020	13	White	Fabric (UC)	High-temperature insulation fabric	Asbestos/glass/polyamide (aromatic type).
163	L-2	0.031	39	Wood grain pattern Smooth	Laminate (SR)	Panels, interior finish	PVC/PVA (95:5) on filled asbestos (71%).
164	S-3	0.070	60	White Glossy	Sheet (R)	Fabricated parts	ABS.

Appendix 3.
Summary of Test Results; Smoke and Gas Concentration

Sample number	Specimen weight	Test Exposure F = Flaming N = Nonflaming	Smoke: Maximum specific optical density D_m	Smoke: Maximum rate R_m	Smoke: Time to $D_s = 16$ t_c	Gas concentration, Maximum indication, Colorimetric tube: CO	HCl	HCN	Others
	g			min^{-1}	min	ppm	ppm	ppm	ppm
1	2.2	F	14	2	NR	50	0	6	
		N	60	19	1.2	30	0	5	
2	1.8	F	72	29	0.5	200	200 S	45	
		N	50	24	0.7	45	150 S	35	
3	2.8	F	60	20	1.0	80	40	15	
		N	89	35	0.9	20	25	10	
4	[a] 2.6	F	16	4	15.0	30	0	0	
		N	6	<1	NR	70	0	0	
5	4.4	F	193	185	0.3	270	150 S	0	
		N	191	30	1.4	80	150 S	0	
6	5.0	F	204	163	0.3	350	200 S	3	
		N	272	28	1.5	400	300 S	2	
7	12.2	F	439	200	0.8	500	90	20	
		N	375	140	1.2	125	30	30	
8	7.0	F	96	50	1.8	140	0	2	
		N	418	60	2.0	800	0	2	
9	9.1	F	380	178	0.5	500	300 S	20	
		N	276	67	1.2	180	80 S	12	
10	7.1	F	>660	340	0.6	260	0	10	$NO+NO_2$:30
		N	76	6	4.3	25	0	8	
11	11.8	F	>660	280	0.7	360	0	10	
		N	167	8	3.5	40	0	9	
12	15.1	F	229	61	1.0	550	1200 S	0	
		N	107	17	3.0	600	800 S	0	
13	5.4	F	289	120	0.6	200	300 S	3	
		N	55	4	6.5	60	250 S	2	
14	4.0	F	139	96	0.6	120	300 S	0	
		N	20	4	3.8	60	250 S	0	
15	[b] 2.6	F	35	6	1.4	50	0	2	
		N	156	9	0.5	50	0	2	

Sample number	Specimen weight	Test Exposure F=Flaming N=Nonflaming	Smoke: Maximum specific optical density D_m	Smoke: Maximum rate R_m	Smoke: Time to D=16 t_c	Gas concentration (Maximum indication, Colorimetric tube): CO	HC1	HCN	Others
16	9.4	F	123	23	1.6	190	0	15	
		N	87	6	2.1	90	0	20	
17	15.2	F	129	50	2.2	320	0	15	$NO+NO_2$:25
		N	206	40	2.0	300	0	60	
18	11.6	F	350	170	1.2	270	30	8	
		N	312	59	2.1	240	6	50	
19	1.7	F	58	10	1.9	150	0	2	
		N	77	13	0.6	45	0	0	
20	13.0	F	76	14	5.2	210	100	2	
		N	22	2	21.6	20	80	0	
21	14.9	F	81	26	2.1	230	200	0	
		N	82	17	5.0	30	100	0	
22	1.3	F	28	4	1.5	90	70	0	
		N	24	4	5.7	10	30	0	
23	[a] 50.0	F	162	11	5.6	500	0	65	$NO+NO_2$:50
		N	105	3	13.6	30	0	2	
24	11.4	F	454	160	0.7	550	1300 S	4	
		N	167	40	1.8	60	1000 S	1	
25	7.2	F	94	9	3.5	320	0	10	
		N	44	6	4.5	80	0	4	
26	6.7	F	50	4	3.7	300	0	8	
		N	43	6	3.6	130	0	7	
27	4.6	F	>660	260	0.8	700	50	25	
		N	126	5	5.3	50	20	8	
28	1.5	F	76	23	0.4	170	150	60	
		N	48	20	0.8	60	150	50	
29	1.6	F	66	23	0.5	200	150	60	
		N	52	17	0.9	40	200	40	

See footnote at the end of table.

Summary of Test Results; Smoke and Gas Concentration—Continued

Sample number	Specimen weight	Test Exposure F = Flaming N = Nonflaming	Smoke: Maximum specific optical density D_m	Smoke: Maximum rate R_m	Smoke: Time to $D_s = 16$ t_c	Gas concentration, Maximum indication, Colorimetric tube: CO	HCl	HCN	Others
	g			min^{-1}	min	ppm	ppm	ppm	ppm
30	12.3	F	63	11	0.6	280	45	7	
		N	45	14	1.9	75	8	1	
31	1.8	F	72	21	0.2	110	110	1	
		N	68	4	3.6	50	90	1	
32	14.7	F	74	15	3.5	150	200	0	
		N	58	6	7.7	50	200	0	
33	17.6	F	458	190	0.7	650	150	20	
		N	207	48	2.4	30	30	5	
34	2.0	F	74	16	0.4	180	80	1	
		N	68	11	1.3	55	60	1	
35	17.4	F	446	200	0.6	750	100	20	
		N	277	74	2.1	35	30	12	
36	17.7	F	>660	240	0.5	850	1300 S	0	
		N	390	40	2.6	30	1000 S	0	
37	18.2	F	641	220	0.7	700	150	50	
		N	156	37	2.9	40	20	5	
38	10.7	F	50	16	1.6	160	0	0	
		N	12	2	NR	30	0	0	
39	12.2	F	460	190	0.6	500	110	20	
		N	146	26	2.3	60	25	6	
40	0.2	F	4	<1	NR	60	0	0	HF:7
		N	1	<1	NR	20	0	0	HF:0
41	15.3	F	448	170	0.4	450	150	20	
		N	181	38	1.5	45	100	5	
42	4.8	F	10	2	NR	150	0	13	
		N	8	<1	NR	130	0	14	
43	21.3	F	8	<1	NR	180	0	18	
		N	4	<1	NR	160	0	15	
44	10.3	F	466	230	0.4	700	300 S	20	
		N	240	120	1.1	180	80 S	12	

Sample number	Specimen weight	Test Exposure F=Flaming N=Nonflaming	Smoke: Maximum specific optical density D_m	Smoke: Maximum rate R_m	Smoke: Time to D_s=16 t_c	Gas concentration, Maximum indication Colorimetric tube: CO	HCl	HCN	Others
45	12.2	F	>660	260	0.4	1000	300	40	
		N	276	65	1.7	150	40	6	
46	12.2	F	303	120	0.8	700	1300 S	1	
		N	172	35	2.0	350	900 S	0	
47	0.7	F	8	1	NR	150	0	1	
		N	8	<1	NR	80	0	0	
48	16.9	F	>660	180	0.5	1200	300	40	
		N	280	130	1.4	400	250	15	
49	21.2	F	518	220	0.7	1200	1600 S	15	
		N	414	100	1.4	250	1200 S	2	
50	•6.2	F	229	110	0.2	700	150	30	
		N	164	59	0.4	200	0	3	
51	17.0	F	>660	250	0.2	1100	400	38	
		N	302	50	0.6	400	400	30	
52	•4.6	F	30	8	2.5	250	0	3	
		N	318	46	0.5	250	0	2	
53	5.9	F	60	23	0.2	230	15	10	
		N	87	34	0.6	90	8	5	
54	4.1	F	24	7	0.8	140	8	6	
		N	56	26	0.4	80	1	7	
55	0.9	F	30	6	2.9	160	50	2	
		N	35	5	3.1	80	35	1	
56	0.6	F	18	3	5.2	120	9	3	
		N	40	3	7.8	50	5	1	
57	1.0	F	27	7	1.3	100	40	1	
		N	40	4	3.9	60	12	1	
58	2.6	F	58	22	1.0	80	40	15	
		N	89	35	1.0	20	25	10	
59	3.0	F	115	64	0.4	250	600	0	
		N	28	8	1.8	100	400	0	

Summary of Test Results; Smoke and Gas Concentration—Continued

Sample number	Specimen weight	Test Exposure F = Flaming N = Nonflaming	Smoke: Maximum specific optical density D_m	Smoke: Maximum rate R_m	Smoke: Time to $D_s = 16$ t_c	Gas concentration, Maximum indication, Colorimetric tube: CO	HCl	HCN	Others
	g			min^{-1}	min	ppm	ppm	ppm	ppm
60	12.8	F	609	260	0.5	1100	1500 S	15	
		N	290	47	1.2	150	800 S	4	
61	12.7	F	600	250	0.5	1000	1400 S	25	
		N	267	77	1.4	130	850 S	8	
62	13.2	F	436	180	0.5	800	700 S	20	
		N	216	33	1.6	320	450 S	5	
63	2.0	F	60	20	0.5	280	150	45	
		N	78	22	0.7	80	100	40	
64	12.1	F	295	140	0.6	380	30	25	
		N	254	92	1.3	160	0	55 d	
65	8.3	F	355	310	0.7	300	0	17	
		N	327	86	2.0	170	0	110 d	
66	5.0	F	199	180	0.4	420	450	0	
		N	180	44	1.4	500	450	1	
67	4.7	F	69	28	0.4	230	20	0	
		N	60	6	4.2	30	8	0	
68	6.7	F	311	160	0.6	500	800 S	0	
		N	246	19	2.4	200	200	0	
69	5.3	F	234	200	0.4	500	800 S	0	
		N	178	33	1.2	190	500	0	
70	5.5	F	295	250	0.4	450	700 S	1	
		N	178	26	1.2	150	300	1	
71	6.0	F	300	230	0.4	450	1100 S	1	
		N	104	25	1.0	280	350	1	
72	14.1	F	>660	260	0.6	1200	800 S	17	
		N	286	45	1.6	130	400	7	
73	20.8	F	574	180	0.6	120[illegible]	400	40	
		N	442	58	2.0	200	200	20	
74	86.9	F							
		N	328	5	9.0	140	0	0	

Sample number	Specimen weight	Test Exposure F=Flaming N=Nonflaming	Smoke: Maximum specific optical density D_m	Smoke: Maximum rate R_m	Smoke: Time to D_s=16 t_c	Gas concentration, Maximum indication, Colorimetric tube: CO	CH1	HCN	Others
75	3.9	F	39	13	0.9	180	0	5	
		N	175	29	1.2	120	0	5	
76	16.0	F	151	35	1.2	220	80	7	
		N	200	70	1.4	100	5	3	
100	32.9	F	383	120	1.9	2200	100	0	
		N	203	12	6.0	400	8	0	
101	0.9	F	10	< 1	NR	70	0	1	
		N	0	0	NR	10	0	1	
102	1.0	F	8	1	NR	95	0	2	
		N	5	< 1	NR	10	0	0	
103	5.7	F	30	6	1.5	330	1600 S	2	
		N	20	2	6.8	110	1300 S	1	
104	9.4	F	25	4	2.8	130	15	5	
		N	25	5	3.0	70	12	4	
105	5.2	F	11	2	NR	110	35	1	
		N	10	1	NR	75	13	0	
106	18.4	F	210	70	2.8	400	0	0	
		N	12	1	NR	50	0	0	
107	1.2	F	39	15	0.4	160	120	35	
		N	41	10	0.8	90	100	30	
108	1.2	F	39	11	0.6	220	110	30	
		N	41	13	0.6	60	100	30	
109	12.4	F	183	66	0.9	270	0	1	
		N	168	5	18.2	120	0	0	
110	23.2	F	>660	220	0.6	1000	1000 S	20	
		N	498	68	2.3	280	700	10	
111	11.0	F	566	310	0.5	1100	600 S	19	
		N	248	42	1.8	180	600 S	8	
112A	11.2	F	40	12	2.6	220	0	0	SO_2: 150
		N	4	< 1	NR	30	0	0	SO_2: 0

APPENDIX I

Summary of Test Results; Smoke and Gas Concentration—Continued

Sample number	Specimen weight	Test Exposure F = Flaming N = Nonflaming	Smoke: Maximum specific optical density D_m	Smoke: Maximum rate R_m	Smoke: Time to $D_s = 16$ t_c	Gas concentration, Maximum indication, Colorimetric tube: CO	HCl	HCN	Others
	g			min^{-1}	min	ppm	ppm	ppm	ppm
113	1.9	F	4	< 1	NR	60	0	0	
		N	4	< 1	NR	5	0	0	
114	1.6	F	9	3	NR	70	25	0	
		N	11	2	NR	20	17	0	
115	0.5	F	0	0	NR	60	0	0	HF: 0
		N	0	0	NR	5	0	0	HF: 0
116	2.3	F	6	< 1	NR	70	0	0	
		N	3	< 1	NR	15	0	0	
117	9.5	F	321	100	0.6	650	2000 S	5	
		N	173	25	1.6	750	1100 S	2	
118D	1.1	F	15	< 1	NR	280	0	1	HF: 11
		N	0	0	NR	< 5	0	0	HF: 0
119	1.0	F	1	< 1	NR	80	0	0	
		N	2	< 1	NR	10	1	0	
120	3.0	F	1	< 1	NR	90	11	0	
		N	1	< 1	NR	10	10	0	
121	12.2	F	14	< 1	NR	170	15	5	
		N	7	< 1	NR	100	13	1	
122	23.0	F	125	30	1.1	800	2500 S	1	
		N	66	13	3.2	700	2000 S	1	
123	•20.0	F	>660	290	0.2	1000	1100	8	SO_2: 45, H_2S: 40
		N	508	120	0.3	500	1500 S	6	SO_2: 40
124	1.9	F	26	8	3.9	150	700	0	
		N	34	4	3.9	20	300	0	
125	0.9	F	2	< 1	NR	60	0	0	
		N	1	< 1	NR	10	0	0	
126	0.9	F	1	< 1	NR	60	0	0	
		N	1	< 1	NR	10	0	0	
127	5.5	F	309	250	0.4	380	700 S	2	
		N	162	45	1.0	100	1000 S	1	

Sample number	Specific weight	Test Exposure F=Flaming N=Nonflaming	Smoke: Maximum specific optical density D_m	Smoke: Maximum rate R_m	Smoke: Time to D_s=16 t_c	Gas concentration, Maximum indication, Colorimetric tube: CO	HCl	HCN	Others
128A	°4.2	F	262	120	0.2	320	150	25	
		N	286	62	0.7	160	25	2	
128B	°3.5	F	41	15	0.6	150	2	2	
		N	300	54	0.7	190	2	2	
129	20.1	F	109	40	1.2	480	0	2	HF: 80
		N	75	28	2.5	20	0	0	HF: 90
130	16.7	F	230	92	0.8	750	400 S	0	SO_2: 50
		N	196	70	1.1	60	200 S	0	SO_2: 40
131	18.8	F	233	130	0.7	550	200	5	
		N	161	42	1.6	100	200 S	2	
132	1.8	F	67	25	0.4	210	150 S	46	
		N	62	28	0.6	90	100 S	37	
133	7.5	F	503	300	0.4	500	800 S	1	
		N	218	57	1.3	80	900 S	0	
134	5.6	F	368	340	0.4	470	600 S	0	
		N	150	29	1.5	70	350 S	0	
135	5.3	F	170	83	0.4	200	600 S	1	
		N	94	30	1.0	70	400 S	1	
136	18.3	F	342	160	0.6	800	900 S	3	
		N	169	47	1.2	250	500 S	1	
137	14.8	F	440	140	0.5	620	1700 S	10	
		N	154	41	1.7	120	800 S	1	
138	1.0	F	10	2	NR	100	0	4	
		N	9	< 1	NR	40	0	2	
139	1.5	F	1	< 1	NR	45	0	0	HF: 26
		N	1	< 1	NR	< 5	0	0	HF: 10
140	2.4	F	50	16	0.8	270	17	8	$NO + NO_2$: 8
		N	51	14	0.9	210	14	5	
141	5.4	F	28	4	5.9	180	0	0	SO_2: 30
		N	1	< 1	NR	< 5	0	0	SO_2: 0

Summary of Test Results; Smoke and Gas Concentration—Continued

Sample number	Specimen weight	Test Exposure F = Flaming N = Nonflaming	Smoke: Maximum specific optic density D_m	Smoke: Maximum rate R_m	Smoke: Time to $D_s = 16$ t_c	Gas concentration (Maximum indication, Colorimetric tube): CO	HCl	HCN	Others
	g			min⁻¹	min	ppm	ppm	ppm	ppm
143	8.6	F	51	10	3.2	700	0	48	{NO+NO$_2$: 10 NH$_3$: 60
		N	65	7	4.8	880	0	40	
144	2.4	F	32	8	2.4	130	0	3	NO+NO$_2$: 12
		N	30	8	3.4	20	0	0	
145	3.6	F	11	2	NR	80	25	1	
		N	14	2	NR	20	15	0	
146	2.3	F	8	<1	NR	140	0	5	NO+NO$_2$: 8
		N	6	<1	NR	10	0	2	
147	42.4	F	>660	88	1.4	2000	120	5	
		N	304	15	4.5	200	20	0	
148A	11.4	F	410	130	0.5	400	1000 S	70	
		N	314	66	1.5	120	300 S	90	
148C	11.5	F	464	190	0.5	500	1000 S	90	
		N	324	150	1.5	100	250 S	90	
149	2.3	F	50	20	1.2	80	300 S	50	
		N	66	30	1.2	50	200 S	60	
150	*4.8	F	101	43	0.4	270	40	12	NO+NO$_2$: 12
		N	205	42	0.4	40	0	2	
151	15.2	F	202	91	0.9	350	900 S	1	
		N	148	45	2.9	40	500 S	0	
152	10.5	F	223	76	0.6	500	1200 S	1	
		N	88	20	1.7	180	300 S	1	
153	1.5	F	19	6	1.1	80	150	15	
		N	25	10	1.1	80	90	20	
154	12.5	F	151	50	0.9	60	0	0	
		N	44	10	2.8	10	0	0	

Sample number	Specimen weight	Test Exposure F=Flaming N=Nonflaming	Smoke: Maximum specific optical density D_m	Smoke: Maximum rate R_m	Smoke: Time to $D_s=16$ t_c	Gas concentration (Maximum indication, Colorimetric tube): CO	HC1	HCN	Others
155		*F*							
		N							
156	1.3	*F*	3	< 1	NR	100	0	0	HF:35
		N	2	< 1	NR	40	0	0	HF:24
157	[a]2.0	*F*	90	130	0.6	130	200	25	
		N	18	4	4.6	20	80	20	
158	5.1	*F*	195	170	0.5	300	150 S	5	
		N	59	25	1.2	35	150 S	1	
159	6.7	*F*	154	[c]4	0.7	240	200 S	0	
		N	63	20	1.5	50	100 S	0	
160	13.1	*F*	190	70	0.7	500	200	0	
		N	106	18	3.3	125	150	0	
161	11.5	*F*	43	18	2.0	110	130	0	
		N	24	8	4.4	25	70	0	
161x	1.5	*F*	52	20	0.3	120	150	0	
		N	29	11	1.0	25	80	0	
162	2.5	*F*	1	< 1	NR	30	0	0	
		N	0	0	NR	< 5	0	0	
163	7.5	*F*	11	< 1	NR	80	150	0	
		N	1	< 1	NR	60	150	0	
163x	6.3	*F*	4	< 1	NR	100	80	0	
		N	0	0	NR	90	40	0	
164	11.8	*F*	>660	260	0.4	500	200	20	
		N	152	54	1.7	40	50	10	

[a] Material not f[illegible] exposed because of melting, shrinking, etc.
[b] Tested in ⅝-i[illegible]ickness.
[c] Tested in 1-in. [illegible]ckness.
[d] Probably acrylonitrile vapor indication.

NR Not reached.
S Measured with chloride ion electrode.

Appendix 4. Typical Smoke Accumulation Curves for Selected Materials

D_s Specific optical density $= \dfrac{V}{AL} \log \dfrac{100}{T}$

F Flaming exposure

NF Nonflaming (smoldering exposure)

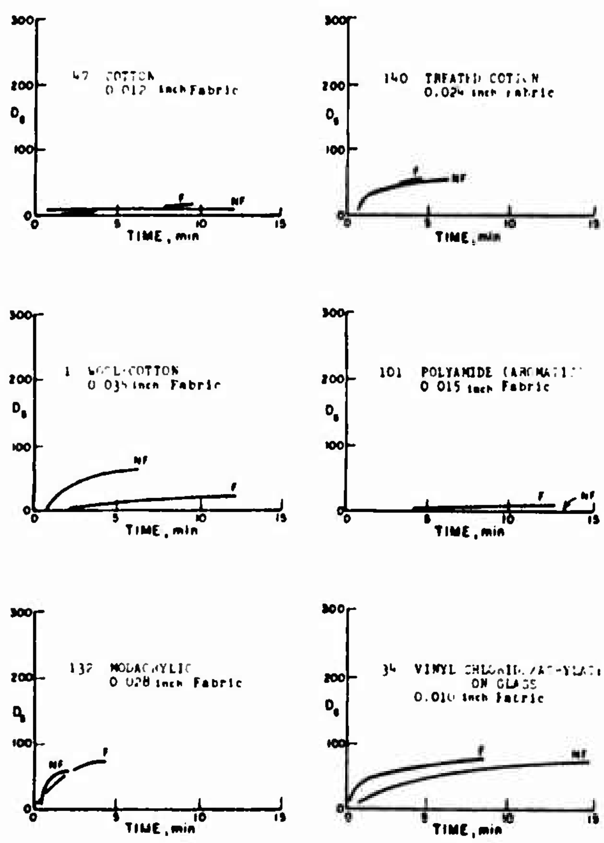


FIGURE 14. *Typical smoke curves—fabrics.*

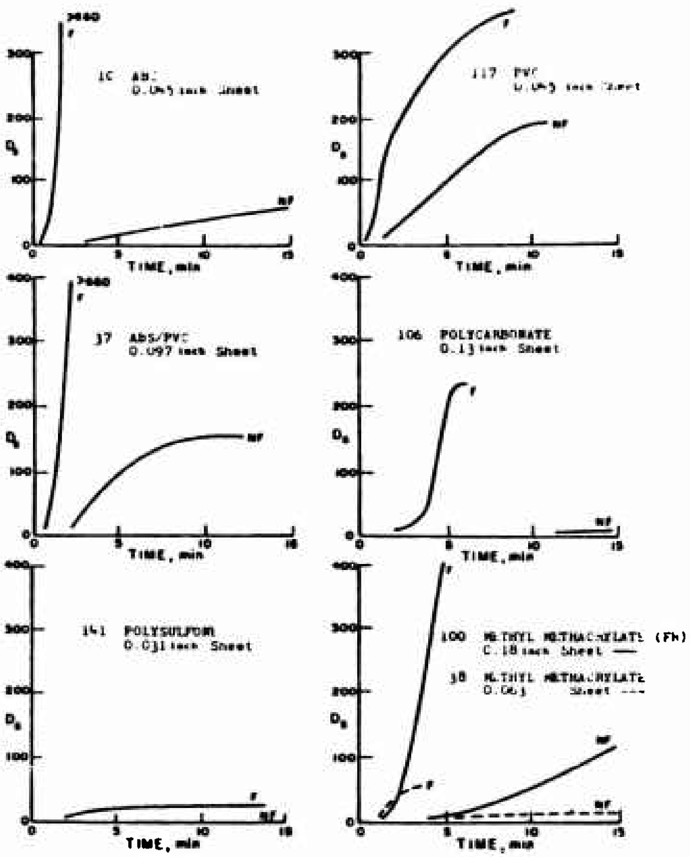


FIGURE 16. *Typical smoke curves—sheets.*

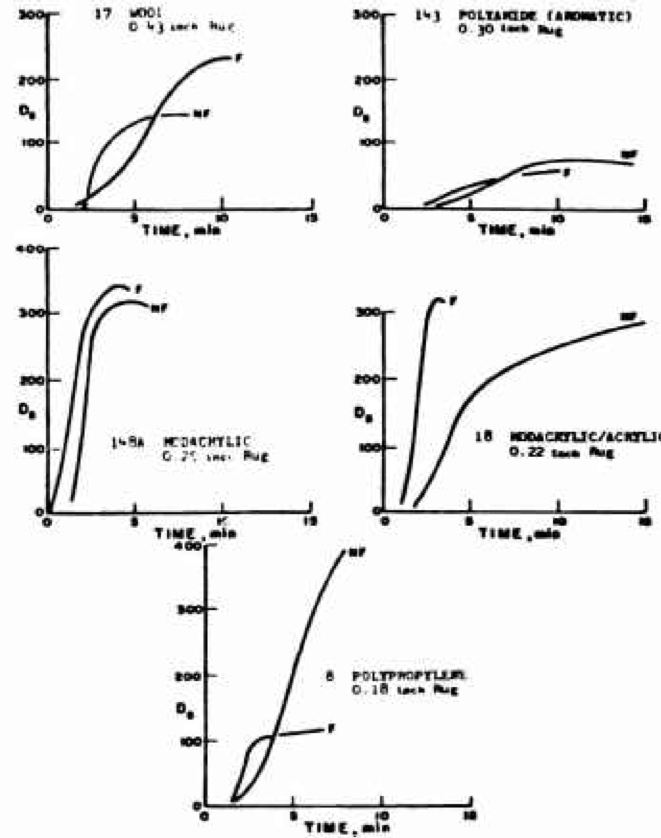


FIGURE 15. *Typical smoke curves—rugs.*

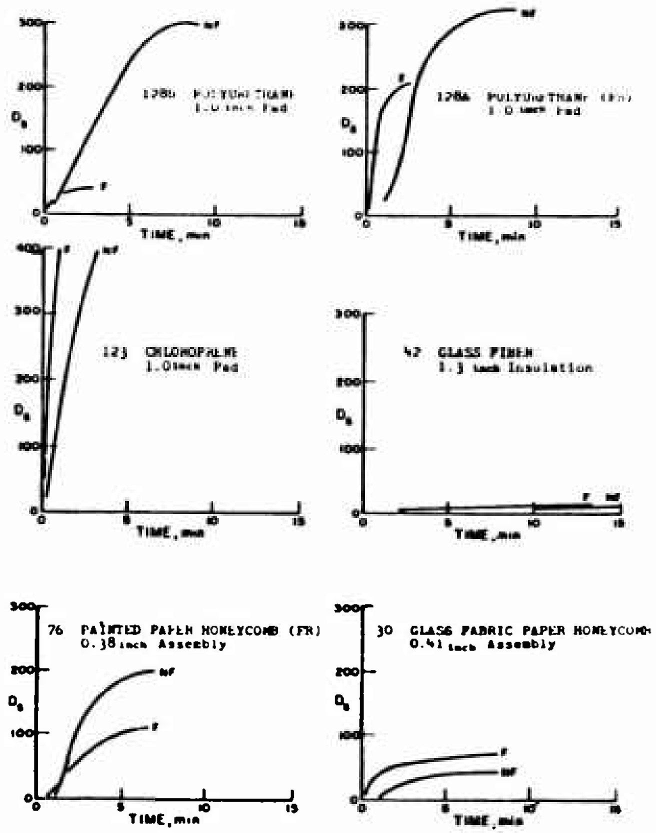


FIGURE 18. *Typical smoke curves—pads, insulation, assemblies.*

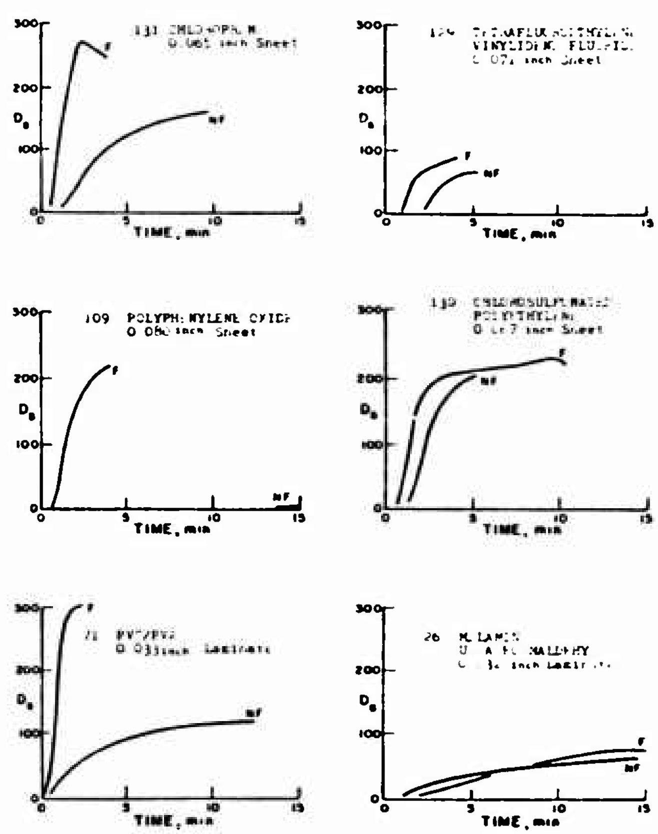


FIGURE 17. *Typical smoke curves—sheets, laminates.*

☆

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3. Gross, D., Loftus, J. J., and Robertson, A. F., A Method for Measuring Smoke from Burning Materials, American Society for Testing Materials Special Technical Publication 422, 1967.

5. Madorsky, S. L., Thermal Degradation of Organic Polymers, 315 pp. (Interscience (Wiley) 1964).

6. Ausobsky, S., Evaluation of the combustion gases in plastics, (in German), VFDB Zeitschrift 16, 58–66, 1967.

7. Coleman, E.H. and Thomas, C. H., The products of combustion of chlorinated plastics, J. Appl. Chem. 4, 379–383, 1954.

8. Fish, A., Franklin, N. H., and Pollard, R. T., Analysis of toxic gaseous combustion products, J. Appl. Chem. 13, 506–9, 1963.

APPENDIX J

COMBUSTION PRODUCTS OF POLYMERS IN FIRES

REFERENCE [1] (Wagner)

In building fires one nearly always encounters pyrolysis and combustion products of cellulosic fuels along with various plastics. Fires are classified according to NFPA categories into four general types [4]:

Class A: Fires involving ordinary combustible materials (wood, cloth, paper, rubber, and many plastics).

Class B: Fires involving flammable or combustible liquids, flammable gases, and greases.

Class C: Fires involving electrical equipment. These are treated as Class A or B fires after the electricity is turned off.

Class D: Fires involving combustible metals. . . .

Since most enclosure fires are of the class A type, involving cellulosic fuels, it is important to consider the different temperature zones since this controls the fire environment. Based on a review by Browne, [5] described by Beall and Eichner, [6] four distinct temperature zones are given for the Thermal Decomposition of Wood as follows:

Zone A: Below 200°C. Appearance of noncombustible gases, primarily H_2O vapor, traces of CO_2, formic and acetic acids, and glyoxal. Dehydration of sorbed water is complete.

Zone B: 200° to 280°C. Same gases as in Zone A are produced along with greatly reduced quantities of water vapor and CO. Reactions are endothermic and products are almost entirely nonflammable.

Zone C: 280° to 500°C. Active pyrolysis takes place under exothermic conditions leading to secondary reactions among the products. Largely combustible products, CO, CH_4, etc., and flammable tars in form of smoke particles.

Zone D: Above 500°C. Residue consists primarily of charcoal, which provides an extremely active site for secondary reactions.

The early combustion stages are similar to the pyrolysis stages, modified slightly by oxidation. These stages are categorized as follows:

Zone A: Similar to Zone A above, but slightly affected by some oxidation processes.

Zone B: Primary exothermic reaction takes place without ignition.

Zone C: Combustible gases that are ignitable are produced after secondary pyrolysis. Flaming combustion can occur in gas phase if the gases are ignited. If ignition is not induced flaming may not occur until near the end of pyrolysis when the evoked gases cannot insulate the charcoal layer from O_2. Spontaneous ignition of charcoal takes place at temperature lower than any of the products evolved.

Zone D: Greater than 500°C the charcoal glows and is consumed; greater than 1000°C nonluminous flames are supported by the combustion of H_2 and CO.

These zones illustrate the complexity of cellulosic combustion processes.

In an enclosure one would expect an agglomeration of both pyrolysis and combustion products. This is illustrated in the flow diagram in Figure 1. Conductive heating will induce pyrolysis. This would be limited to the percolation of gases through materials that leave porous char-like residues. Radiation and convective heat transfer are primarily responsible for flame spreading and are longer range. The liquid and solid phases are also present in varying degrees.

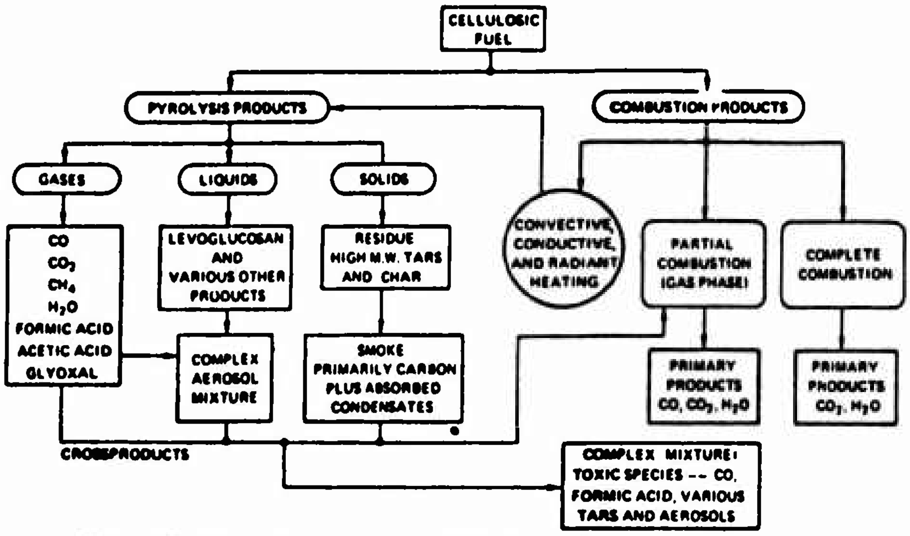

FIG. 1. Flow diagram for pyrolysis and combustion of cellulosic fuels in an enclosure.

An enclosure fire of plastics can be represented by the simplified flow diagram in Figure 2. Common plastics are designated by -C-H-O-N- type structural

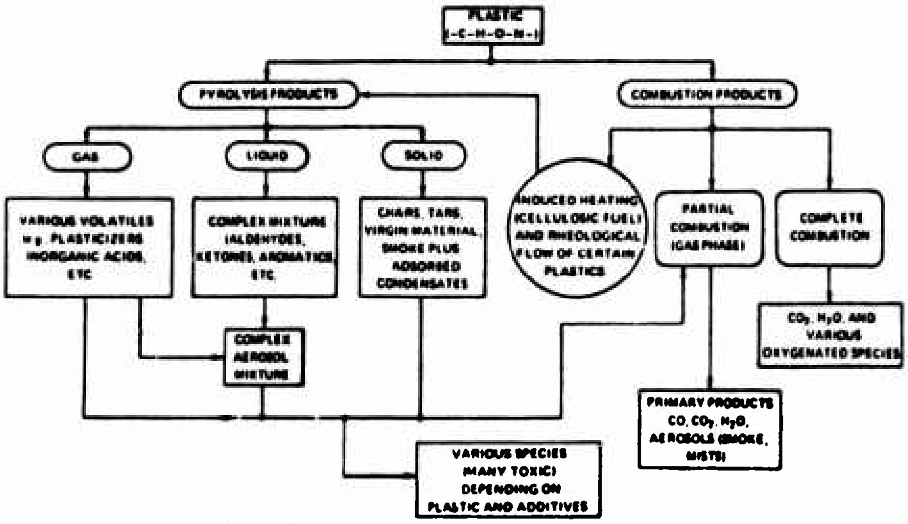

FIG. 2. Flow diagram for pyrolysis and combustion of plastics in an enclosure.

arrangements. Pyrolysis can result from the cellulosic fuels and also from self-induced modes of heating. In addition to the flame-spread mechanisms common to cellulosic fuels a rheological flame spread mechanism occurs with thermosetting plastics. Here molten or flaming drops or even streams of these fluids can drastically alter flame spread mechanisms and require evacuation and extinguishment techniques.

Both pyrolysis and combustion of plastics must be considered as equally important in light of recent studies that indicate many plastics formerly considered self-extinguishing can be burnt continuously from below (bottom burning) by incorporation of a noncombustible wick. [7] Wicking action is nearly always provided by the contents of an enclosure. The chemical and physical modifications of plastics, the incorporation of additives along with the thousands of trade names [8] make it exceedingly difficult to generalize the products as with cellulose fuels. A breakdown into groups such as char formers, vapor formers, and combined effects such as charrers plus vapor formers is helpful. . . . [Summary discussion of certain polymers later in article.]

References

4. Fire Protection Handbook, National Fire Protection Association, 13th ed., 1969.

5. F. L. Browne, Theories on the Combustion of Wood and its Control, U. S. Forest Products Laboratory, Rept. 2136, Madison, Wisconsin, 1958.

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APPENDIX K

EVALUATING THE HAZARD OF TOXIC FUMES AND SMOKE:

Selected Examples of Various Methods

Example of Analytical Method

Excerpt from I. N. Einhorn, *et al.,* "Physiological and Toxicological Aspects of Smoke Produced During the Combustion of Polymeric Materials," Proceedings of the NSF/RANN Conference on Fire Research (Washington, D. C. UTEC-MSE 74-083, FRC/UU-29, June 21, 1974., p. 199

Task 6 — Effect of Fire Retardants on Smoke and Degradation Products [Excerpt]

To date, the major concern of those engaged in the development of fire retardant materials has been the reduction of the ignition tendency and flame propagation. Thus, it has been possible to meet code and regulatory requirements regarding flame spread. However, it is our opinion that the total hazard resulting from incomplete combustion may actually have been increased. A study of several recent fires, in which fire-retarded plastics were involved has indicated that smoke development and the production of copious amounts of toxic decomposition products have resulted in bodily injury or loss of life long before the spread of fire has reached those individuals trapped in the conflagration.

The Mettler Thermoanalyzer has been used to conduct experiments on the effects of environment, heating rate, and % fire retardant in urethanes. Figure 9 shows dynamic TGA curves at different bromine fire-retardant concentrations with rigid-urethane foam.

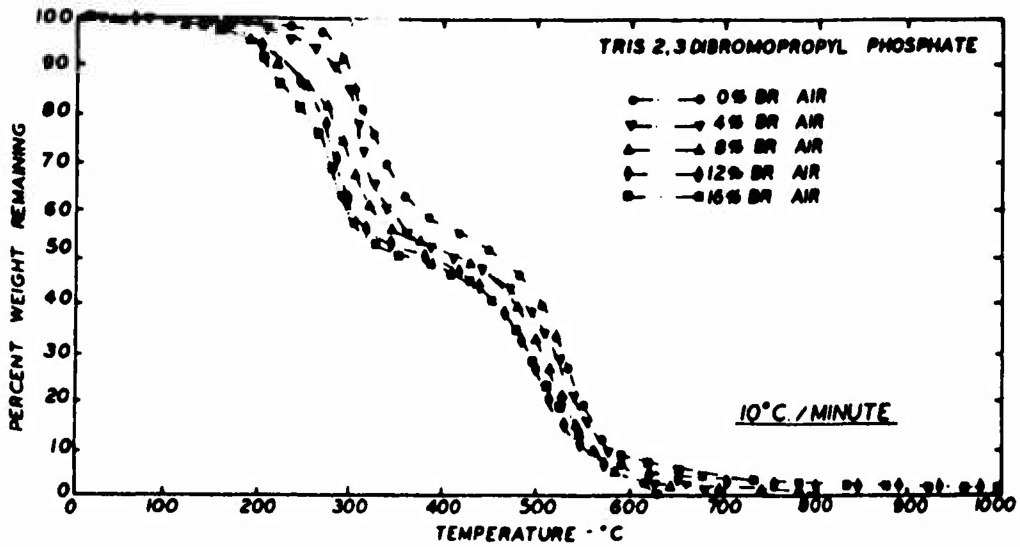

Figure 9. Effect of Fire Retardant Concentration on Thermal Degradation

[Note: TGA = thermal gravimetric analysis]

APPENDIX K

Example of Biological Method

Excerpt from R. E. Reinke and C. F. Reinhardt, "Fires, Toxicity, and Plastics," *Modern Plastics,* 50 (1973): 94-5, 97-8.

Table V: Toxicity results from thermodegradation products of polymers

Part 1: Series of 15-min. exposures using 3 g. of foamed materials, 30 g. of all other materials. Pyrolysis temperatures up to 1364° F. (12).

Material	Mortality for mice[a]
Polystyrene rigid foam (A or B)	0/10
Phenolic rigid foam	0/5
Wood-wool cement board	1/5
Acrylic rigid sheet	4/5
Wood (cedar)	5/5
Fire-retardant plywood	5/5
Melamine laminate	5/5
Polyvinyl chloride rigid sheet	5/5
Polyurethane rigid foam	5/5

Part 2: Series of exposures (13):
No. 1. 6-hr. exposure, 4.7 to 5.5-g. sample.
No. 2. 6-hr. exposure, 5.7 to 6.8-g. sample.
No. 3. 10-min. exposure, 2.0-g. sample.

	Mortality for rats[a]		
	No. 1, 392° F.	No. 2, 482° F.	No. 3, 1040° F.
Polyurethane A	0/4	1/4	0/2
Polyurethane B	0/4	1/4	0/2
Polyurethane C	0/4	0/4	0/2
Neoprene	0/4	1/4	0/2
Rubber latex	0/4	4/4	0/2
Polyvinyl chloride	2/4		1/2

Part 3: Series of 30-min. exposures, 5-g. samples (14).

	Mortality for rats[a]			
	572° F.	752° F.	932° F.	1112° F.
Polystyrene A	0/12	0/12	0/18	11/12
Polystyrene B or C	0/24	0/24	25/42	24/24
4 other PS	0/48	0/48	48/48	48/48
Expanded cork	0/12	5/18	12/12	12/12
Rubber	0/12	12/12	12/12	12/12
Wool	2/12	12/12	12/12	12/12
Pine wood	3/12	12/12	12/12	12/12
Felt	6/12	12/12	12/12	12/12
Leather	12/12	12/12	17/18	11/12

Part 4: Series of 30-min. exposures, 5-g. samples (14).

	Mortality for rats[a]				
	392° F.	572° F.	752° F.	932° F.	1112° F.
Polyethylene	0/12	0/12	12/12	12/12	12/12
Fir	0/12	13/18	12/12	12/12	12/12
PVC	0/12	10/12	11/12	12/12	12/12
Celluloid	12/12	12/12	12/12	12/12	12/12

a—Mice or rats exposed to products resulting from pyrolysis temperatures indicated. Figures in table show ratio of number of mortalities to number exposed. All temperatures have been converted to °F.

References from Reinke and Reinhardt

12. K. Kishatani, J. Fac. Engr. Univ. of Tokyo (B) 21.1 (1971).

13. J. A. Zapp, Jr., Arch, Environ., Health 4, No. 3.335 (1962).

14. H. Th. Hoffmann and H. Oettel., Modern Plastics 46. 94 (Oct. 1969).

Example of "Combined Analytical and Biological Method

Excerpt from G. Kimmerle, "Aspects and Methodoloty for the Evaluation of Toxicological Paremeters During Fire Exposure," *Journal of Fire and Flammability-/Combustion Technology 1* (1974): 4-51

Table 51. Toxicity of the Pyrolysis Products of Polyisocyanurate Foams in Rats Tests with Equal Volume (300 by 10 to 5 mm) [12]

Sample	Fire Retardant	Temp °C	CO ppm	HCN ppm	CO H_b	Number of Deaths Out of 20
1	No	500	1,100	150	43.5	0
		550	3,000	150	58.9	13
2	Yes	550	1,600	130	43.3	0
		600	2,000	150	52.3	9
3	Yes	600	1,200	75	32.8	0
4	Yes	500	470	25	17.6	0
		600	1,230	100	44.7	3
5	Yes	500	500	45	29.6	0
		550	1,300	120	47.6	11
6*	Yes	500	930	55	27.9	0
		600	1,670	125	48.5	1

*Sample of polyisocyanurate foam reinforced with foamed glass pellets.

Table 52. Toxicity of the Pyrolysis Products of Rigid Isocyanurate Foams in Rats Tests with Equal Weight (1.2 Grams per 100 mm) [12]

Sample	Fire Retardant	Temp °C	Concentration in Air CO ppm	HCN ppm	CO H_b	Number of Deaths Out of 20
1	No	400	1,000	50	33.6	0
		450	2,800	150	58.2	19
2	Yes	350	1,100	50	23.7	0
		400	3,500	150	39.2	15
3	Yes	350	800	50	19.4	0
		400	2,500	150	39.2	14
4	Yes	300	450	10	17.0	0
		350	1.470	45	42.6	4
5	Yes	300	300	10	12.5	0
		400	2,150	150	52.6	12

First occurrence of mortalities: by volume 550° and 600° C
sometimes none at 600° C

by weight 350°, 400°, and 450° C

[12]Kimmerle, Unpublished results 1972-1973, Bayer AG, Institut fur Toxikologie, Werk Wuppertal, Germany.

Most of the mortalities can be related to the combined action of carbon monoxide and hydrogen cyanide, but in the case of sample 5, other toxic gases must have caused a more important effect.

Example of Epidemiological Method

Excerpt from B. A. Zikria, *et al.*, "Smoke and Carbon Monoxide Poisoning in Fire Victims," Journal of Trauma, 12 (1972): 641-5

TABLE I

Burn Mortality, New York City (1966 and 1967)

Total Victims 534 (Survival Time)			Autopsied Victims 311	
PBST	Cases	Per Cent	No. Cases	Per Cent
< 12 hr	283	53	185	60
> 12 hr	158	30	72	23
Not known	93	17	54	17
Total	534	100	311	100

TABLE II

Respiratory Involvement in 257 Autopsied Victims

	PBST 12 hr (Survival Time)		PBST 12 hr (Survival Time)	
	Cases	Per Cent	Cases	Per Cent
Smoke poisoning or asphyxia only	99	53.5	4	5.6
Resp. tract pathology	11	5.9	28	38.9
Both	20	10.8	1	1.4
Neither	55	29.9	39	54.1
Total	185	100.0	72	100.0

TABLE III

Respiratory Tract Pathology in 60 Autopsied Victims with 66 Attributions

Pathology	Attrib.	BSAB (aver.)	(DOA) PBST < 12 hr	(Aver. Surv.) PBST > 12 hr
Tracheobronchitis	13	41%	5 (5)	8 (12 days)
Penumonia/pneumonitis	31	45%	9 (8)	22 (21 days)
Pulmonary/edema/congestion	22	67%	17 (16)	5 (4 days)
Lung abscess	1	0%	0 (0)	1 (46 days)
Other*	9	34%	5 (4)	4 (22 days)

* Emphysema, empyema, bronchiectasis, fibrosis, pulmonary embolus.

TABLE IV

Carbon Monoxide Poisoning in 185 Autopsied Victims, with Death Occurring Under 12 Hr

	Carboxyhemoglobin Sat.	Cases	Per Cent
Laboratory determination		(130)	(70.3)
Usually lethal	> 50%	45	24.3
Significant	11%-49%	64	34.6
No contribution	0%-10%	21	11.4
Clinical diagnosis only		14	7.6
No indication		41	22.1
Total		185	100.0

TABLE V

Carbon Monoxide Poisoning in 72 Autopsied Victims with Death Occurring Over 12 Hr

	Carboxyhemoglobin Sat.	Cases	Per Cent
Laboratory determination		(4)	(5.5)
Usually lethal	> 50%	0	0.0
Significant	11%-49%	1	1.4
No contribution	0%-10%	3	4.1
Clinical diagnosis only		4	5.5
No indication		64	89.0
Total		72	100.0

[PBST = postburn survival time]

Another Example of Epidemiological Method

Excerpt from R. M. Fristrom, "Smoke Injury Studies," Proceedings of the NSF/RANN Conference on Fire Research, June 21, 1974. pp. 62-73.

TABLE 1
CARBON MONOXIDE AND CORONARY VASCULAR DISEASE AS CAUSES OF DEATH
107 FIRE FATALITIES

CAUSE	NUMBER	PERCENT
CO ALONE	48	45%
CO + CORONARY DISEASE	35	33%
CO + BURN	5	5%
CORONARY DISEASE ALONE	2	2%
BURN ALONE	15	14%
UNCERTAIN	2	2%

TABLE 2
CARBOXYHEMOGLOBIN AND BLOOD ALCOHOL
CASES AGE 18 AND OVER

BLOOD ALCOHOL gm/100m1	COHB% > 40	COHB% 20-40	COHB% < 20	TOTAL	%
NONE	22	3	10	35	(44%)
< 0.05	0	1	1	2	(3%)
0.05-0.15	13	0	1	14	(18%)
0.16-0.25	11	4	4	19	(24%)
> 0.25	7	1	1	9	(11%)
	53	9	17	79	(100%)

CASES UNDER AGE 18
(NO ALCOHOL PRESENT)

	COHB% > 40	COHB% 20-40	COHB% < 20	TOTAL
	23	2	3	28
TOTAL ALL CASES	76	11	20	107

TABLE 3
FACTORS RESPONSIBLE FOR
FAILURE TO ESCAPE FROM FIRES

REASON FOR FAILURE TO ESCAPE	ATTEMPT TO ESCAPE			TOTAL	%
	YES	NO	UNDETERMINED		
CARBON MONOXIDE ALONE	23	6	3	32	29.9%
CARBON MONOXIDE + ALCOHOL	31	6	0	37	34.6%
ALCOHOL ALONE	3	0	0	3	2.8%
BURN (INCL. RESPIRATORY)	5	0	0	5	4.7%
CORONARY OCCLUSION	2	1	0	3	2.8%
INFANT	1	12	0	13	12.1%
INVALID	1	3	0	4	3.7%
EXPLOSION	0	3	0	3	2.8%
CLOTHING FIRES (GENERALLY SUICIDES)	2	3	0	5	4.7%
SUICIDE	0	1	0	1	0.9%
CAR ACCIDENT	0	0	1	1	0.9%
	68	35	4	107	
	(63.6%)	(32 7%)	(3 7%)		

APPENDIX L

MEMORANDUM FROM RALPH C. WANDS

ON FIRE TOXICOLOGY -- A PERSPECTIVE

BIBLIOGRAPHIC DATA SHEET	1. Report No. NMAB 318-6	2.	3. Recipient's Accession No.
4. Title and Subtitle "Aircraft: Civil and Military"			5. Report Date 1976
			6.
7. Author(s) Committee on Fire Safety Aspects of Polymeric Materials			8. Performing Organization Rept. No. NMAB 318-6
9. Performing Organization Name and Address National Materials Advisory Board Commission on Sociotechnical Systems National Research Council 2101 Constitution Ave., N. W., Washington, D.C., 20418			10. Project/Task/Work Unit No.
			11. Contract/Grant No. 903-74-C-0167 DoD 4-35856 NBS
12. Sponsoring Organization Name and Address Department of Defense, Washington, D. C. National Aeronautics and Space Administration, Washington, D. C. National Bureau of Standards, Washington, D. C.			13. Type of Report & Period Covered Final Report
			14.
15. Supplementary Notes			

16. Abstracts

A study has been made of fire safety aspects of polymeric materials used in military and civil aircraft. After a preliminary system analysis, fire incident scenarios based on actual experience (but not reproducing any single fire) were devised. The problem of human survival in case of aircraft fire were assessed in terms of materials, test methods used to evaluate materials, smoke and toxicity, fire dynamics, and design use of materials. Conclusions are drawn in each chapter and appropriate implementable recommendations made. The majority of recommendations are extracted and combined in Chapter 2.

17. Key Words and Document Analysis. 17a. Descriptors

Aircraft
Aircraft Cabins
Fires
Toxicology
Smoke
Scenarios
Adhesives and Seals
Coatings, Colorants, and Finishes
Composite Materials
Fibers and Textiles
Plastics
Rubbers

17b. Identifiers/Open-Ended Terms

Fire Resistance
Fire Tests
Fire Safety
Fire Protection
Fire Resistant Materials
Fire Dynamics

17c. COSATI Field/Group

18. Availability Statement Approved for public release and sale. Distribution is unlimited.	19. Security Class (This Report) UNCLASSIFIED	21. No. of Pages 325
	20. Security Class (This Page) UNCLASSIFIED	22. Price

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10. **Project/Task/Work Unit Number.** Use the project, task and work unit numbers under which the report was prepared.

11. **Contract/Grant Number.** Insert contract or grant number under which report was prepared.

12. **Sponsoring Agency Name and Mailing Address.** Include zip code. Cite main sponsors.

13. **Type of Report and Period Covered.** State interim, final, etc., and, if applicable, inclusive dates.

14. **Sponsoring Agency Code.** Leave blank.

15. **Supplementary Notes.** Enter information not included elsewhere but useful, such as: Prepared in cooperation with . . . Translation of . . . Presented at conference of . . . To be published in . . . Supersedes . . . Supplements . . . Cite availability of related parts, volumes, phases, etc. with report number.

16. **Abstract.** Include a brief (200 words or less) factual summary of the most significant information contained in the report. If the report contains a significant bibliography or literature survey, mention it here.

17. **Key Words and Document Analysis. (a). Descriptors.** Select from the Thesaurus of Engineering and Scientific Terms the proper authorized terms that identify the major concept of the research and are sufficiently specific and precise to be used as index entries for cataloging.
(b). Identifiers and Open-Ended Terms. Use identifiers for project names, code names, equipment designators, etc. Use open-ended terms written in descriptor form for those subjects for which no descriptor exists.
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ADVISORY CENTER ON TOXICOLOGY

7 March 1975

To: Dr. Robert Shane

From: Ralph C. Wands RCW

Subject: Fire Toxicology - A Perspective

The following is the gist of my informal remarks presented at the request of Bernard Achhammer, NASA Polymer Program Manager, at the "PreFiremen" Program Review on January 20, 1975 at NASA Headquarters.

Gentlemen, thank you for altering your agenda to permit me to rejoin the meeting of our Executive Committee this noon. My remarks this morning are not only informal and extemporaneous but also are personal views and are not official policies of the National Academy of Sciences.

The National Academy of Sciences, National Research Council, is a private, non-profit organization operating under an 1863 Congressional Charter. The Charter calls for the Academy to do two things: promote science and technology in the U.S. and maintain a pool of the nation's scientific and technical manpower so that they may be called upon to provide advice on matters of science and technology upon request from the Federal Government. As such, NASA and FAA are able to call upon the NAS/NRC for assistance in such matters as the fire aspects of high polymers. Within the NRC is a Committee on Toxicology and its supporting Advisory Center on Toxicology of which I am the Director. We have a long-standing contract with the Office of Naval Research on behalf of several Federal agencies including those represented here this morning.

We have been involved somewhat peripherally in the program of the NRC's National Materials Advisory Board on fire aspects of high polymers. We have also from time to time advised various of our sponsoring agencies on the toxicology aspects of fire situations, and we currently have a project for FAA on the toxicology of materials of construction for aircraft lavatories which we are told is a frequent source of aircraft fires.

The field of fire toxicology is an infant art and is far from being a well developed science or technology. There are a few practitioners scattered around the world and they are doing some very interesting things and finding some unusual results. There is at this time only poor communication between those people and with the rest of the scientific community. Their techniques are all different and thus the data are difficult to compare.

APPENDIX L

Dr. Robert Shane 7 March 1975

I need not tell this group of fire experts how variable fires are, differing as they do between fires and differing from moment to moment in any given fire. This is the first hurdle confronting a would-be fire toxicologist, what fire conditions does he use to generate the smokes and gases whose toxic effects he wishes to characterize. Even given a series of standard fire test conditions, which we do not have, the toxic products are an unknown mixture which may be constantly changing. At the present time the field of toxicology knows very little about how to test or to evaluate data on mixtures of gases. We are making some progress on simple mixtures of carbon monoxide with one other experimental gas but we are not far along even on that simplistic approach.

One other major variable confronting fire toxicologists is that fire exposures of people, which is why we do this at all, are often of very short duration and usually to high concentrations. Human physiology, especially respiratory physiology, is not well characterized for these conditions.

In very recent times we have begun to learn that fires involving high polymers can lead to some extremely unusual and unexpected materials apparently having highly toxic properties.

The net result of all of this is that the science and art of toxicology is poorly equipped to help the materials and design engineers to select high polymers, plastics and elastomers, for good performance coupled with good safety. There are a few materials about which we know a little but the plastics industry is far ahead of our meagre store of knowledge.

We need someone to take the lead in coordinating efforts in this field, to stimulate research. In particular we need to (1) develop fire toxicology methods suitable for this special kind of materials evaluation, (2) develop an understanding of the chemistry, the biochemistry and physiology, and the bio-kinetics of fire toxicology, (3) develop guidelines for the interpretation of fire toxicology data.

When we have accomplished those things we will then be in a position to assist you people in your "trade-off" decisions of materials performance characteristics vs their fire toxicology aspects. This will always be a probabilistic judgement and should be a multidisciplinary matter.

I can assure you that the NAS/NRC is ready and willing to explore in detail if it can be of assistance and if so how best.